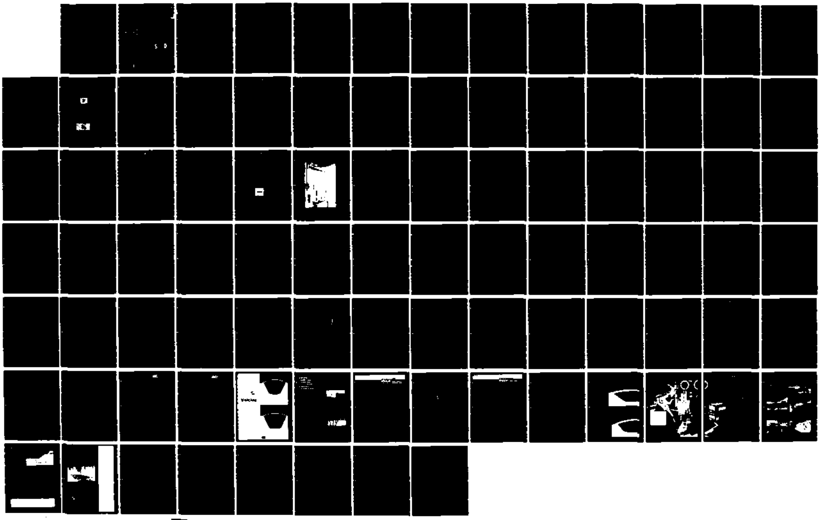
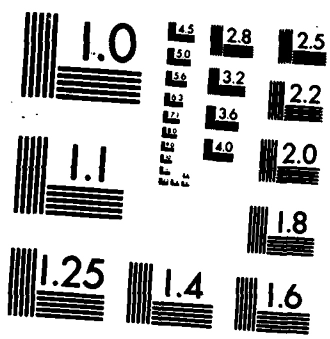
AD-A173 104 LABORATORY STUDY ON EFFECTIVENESS OF CLAY LINERS TO CONTAIN TRICHLOROETHY..(U) WESTON (ROY F) INC WEST CHESTER PA A DASGUPTA ET AL. JUL 86 AMXTH-TE-CR-86075 1/1

UNCLASSIFIED DAAK11-82-C-0017 F/G 8/13 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(2)

Report No. AMXTH-TE-CR 86075

AD-A173 104

Installation Restoration General Environmental Technology Development

Contract DAAK11-82-C-0017

Task Order 10
Laboratory Study on Effectiveness of Clay Liners to Contain Trichloroethylene (TCE) Contaminated Soils Sharpe Army Depot, California

July 1986

"Original contains color plates: All DTIC reproductions will be in black and white"

Distribution Unlimited: Approved for Public Release

Prepared for:
Commander
U.S. ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
Aberdeen, Maryland

WESTON
MANAGERS DESIGNERS/CONSULTANTS
Roy F. Weston, Inc.
West Chester
Pennsylvania 19380

LABORATORY STUDY ON EFFECTIVENESS OF CLAY LINERS
TO CONTAIN TRICHLOROETHYLENE
CONTAMINATED SOILS AT THE
SHARPE ARMY DEPOT, CALIFORNIA

Prepared for:

U.S. Army Materiel Command (AMC)
U.S. Army Toxic and Hazardous Materials Agency (USATHAMA)
Aberdeen Proving Ground, Maryland 21010

Contract No. DAAK11-82-C-0017
Task Order No. 10

Prepared by:

Roy F. Weston, Inc.
Weston Way
West Chester, Pennsylvania 19380

July 1986

W.O. 2281-01-10

5392A

DISCLAIMER

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
AMXTH-TE-CR86075

2. GOVT ACCESSION NO.
AD-A173104

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
Installation Restoration General Environmental Technology Development. Task 10 Laboratory Study on Effectiveness of Clay Liners to Contain Trichloroethylene (TCE) Contaminated Soils, Sharpe Army Depot, California

5. TYPE OF REPORT & PERIOD COVERED
Final Report
January 1985 - July 1986

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Avijit Dasgupta, Ph.D.
David Russell
Peter J. Marks

8. CONTRACT OR GRANT NUMBER(s)
DAAK11-82-C-0017

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Roy F. Weston, Inc.
Weston Way
West Chester, PA 19380

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Army Toxic & Hazardous Materials Agency
Aberdeen Proving Ground
Edgewood Area, MD 21010

12. REPORT DATE
July 1986

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
~~Distribution limited to U.S. Government Agencies only, for protection of privileged information evaluating another command (date published). Other requests for this document must be referred to CDR, USATHAMA, APG, MD 21010-5401~~

See Cover

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
Contract Project Officer - Ms. Donna L. Koltuniak
(AMXTH-TE-D)

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Clay Liner, Permeability, Trichloroethylene (TCE), Liner Campatibility, Organic Solvent, Flexible Wall Permeater

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Laboratory investigations were conducted to evaluate the effectiveness of compacted clays as liner material to contain trichloroethylene (TCE) contaminated soils. Three types of clays were evaluated: Tests were conducted with water and a concentrated solution of TCE and the permeabilities were compared. The results indicated a significant decrease in permeability when the water saturated clays were exposed to TCE. Several potential factors that can cause the permeability decrease were identified and further investigations were recommended.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

CONTENTS

			Page
		FIGURES	iii
		TABLES	iv
		EXECUTIVE SUMMARY	v
Paragraph	1	INTRODUCTION	1
	1.1	Background	1
	1.2	Objectives	1
	1.3	Programmatic framework	1
	2	BACKGROUND INFORMATION	2
	2.1	Previous studies	2
	2.2	Soil characteristics	13
	3	PARAMETERS AND TEST CONDITIONS	15
	3.1	Test parameters	15
	3.2	Test conditions	15
	4	TEST APPARATUS	18
	4.1	Background	18
	4.2	Test apparatus	20
	5	SAMPLING AND ANALYSIS	23
	5.1	Soil sampling	23
	5.2	Soil characteristics	23
	5.3	Soil preparation and handling	25
	5.4	Permeant	25
	6	EXPERIMENTAL PROTOCOL	26
	6.1	Background	26
	6.2	Test procedure	26
	6.2.1	Sample mounting	26
	6.2.2	Assembly of the permeameter	27
	6.2.3	Sample saturation	27
	6.2.4	Permeability test	28
	6.2.5	Calculation of permeability	29
	6.2.6	Termination criteria for the permeability tests	29
	6.3	Quality assurance	31
	6.4	Safety plan	32
	6.5	Contingency plan	33
	7	RESULTS AND DISCUSSION	34
	7.1	Phase 1 investigation	34
	7.2	Phase 2 investigation	43
	7.3	Discussion of findings	51
	7.4	Conclusions	58
	7.5	Recommendations	59

APPENDIX A - CHEMICAL RESISTANCE OF VOLCLAY
APPENDIX B - REFERENCES

FIGURES

			Page
FIGURE	1.	Schematic diagrams of rigid-wall and flexible-wall parameters	4
	2.	Permeability Curves of four clay soils treated with water and organic solvents	7
	3.	Schematic of the clay liner permeability test apparatus	19
	4.	Clay liner permeability test apparatus (flexible wall permeameter)	21
	5.	Photograph of the test apparatus for clay liner permeability studies	22
	6.	Parameters used for calculating permeability	30
	7.	Local clay: permeability trends at high lateral pressure	39
	8.	Soil and Volclay: permeability trends at high lateral pressure	40
	9.	Kaolinite: permeability trends at high lateral pressure	41
	10.	Permeability trends of different clays at high lateral pressure	42
	11.	Local clay: permeability trends at low lateral pressure	47
	12.	Soil and Volclay: permeability trends at low lateral pressure	48
	13.	Kaolinite: permeability trends at low lateral pressure	49
	14.	Permeability trends of different clays at low lateral pressure	50
	15.	Local clay: effect of lateral pressure on permeability	55
	16.	Soil and Volclay: effect of lateral pressure on permeability	56
	17.	Kaolinite: effect of lateral pressure on permeability	57

WESTON

TABLES

		Page
TABLE 1.	Studies on hazardous material/clay liner compatibility	3
2.	Characteristics of commonly used clay soils	9
3.	Physical and chemical properties of common organic fluids	10
4.	Permeabilities and octanol/water partition coefficients for solvents on three clay soils	11
5.	Analysis of experimental variables	16
6.	Soil characteristics	24
7.	Permeability test results -- local clay, high pressure	35
8.	Permeability test results -- soil and Volclay, high pressure	36
9.	Permeability test results -- kaolinite, high pressure	37
10.	Permeability test results -- local clay, low pressure	44
11.	Permeability test results -- soil and Volclay, low pressure	45
12.	Permeability test results -- kaolinite, low pressure	46
13.	Comparison of permeability at low and high pressure test conditions -- local soil and Volclay	52
14.	Comparison of permeability at low and high pressure test condition -- local clay	53
15.	Comparison of permeability at low and high pressure test conditions - Kaolinite	54

EXECUTIVE SUMMARY

This document describes the laboratory investigation conducted to evaluate the effectiveness of clay soils as liner material to contain trichloroethylene (TCE) contaminated soils. This study is a part of the research and development project of the United States Army Toxic and Hazardous Materials Agency (USATHAMA) aimed at determining a suitable technology for treatment and disposal of TCE contaminated soils from the Sharpe Army Depot (SHAD) in Lathrop, California.

The investigation entailed the evaluation of three types of soils as potential liner materials for containing TCE contaminated soils. The three types of soils evaluated were:

(a) Locally available clay near the SHAD site.
(b) A mixture of the local bentonite soil around the SHAD area and a commercially available admixture.
(c) Commercially available kaolinite.

Emphasis was placed on evaluating locally-available soil types to minimize costs of importing material to construct the liner.

The approach which was followed for the bench-scale testing was to expose the soil samples (i.e., liner material) to the chemical "leachate" which could be produced by the contained soils. The soil samples were placed in a permeameter apparatus and subjected to infiltration by the test liquids or permeants. A clay soil could be considered as a suitable candidate for use as a liner material from a chemical compatibility standpoint if it did not exhibit a significant increase in permeability when exposed to the trial leachate liquid. To establish the baseline permeability for the evaluated material, the permeability using distilled water as the permeant was first determined. The sample was then tested in the permeameter using the chemical or leachate permeant.

For purposes of this laboratory investigation, a concentrated solution (~100 percent) of commercial grade TCE was used as the permeant for the leachate. The basis for this selection was to evaluate a "worst-case" scenario with respect to permeant (i.e., leachate) concentration. Literature information and the work of other researchers has indicated that organic solvents may have a detrimental effect on clay permeability. However, little research has been done using the organic solvent TCE.

The test apparatus for the investigation was a flexible-wall permeameter which utilized an inner Teflon membrane with an outer latex membrane to surround the soil test sample. Teflon was selected as the inner membrane material to avoid possible dissolution of the latex membrane when in contact with the TCE permeant. The choice of this type of permeameter was an important aspect in the investigation since two types of permeameters are commonly used for such studies, namely, the rigid-wall and flexible-wall types. Based on literature review and experience, it was concluded that the flexible-wall type permeameter better simulates the stresses under field conditions, particularly the lateral/overburden pressure which cannot be simulated in the rigid-wall type permeameter. Moreover, with the rigid-wall type, side-wall effects created by shrinkage of the soil due to organic solvents may yield erroneous results.

The test procedure basically consisted of permeating the TCE through the soil sample and noting the time taken for different pore volumes of the permeant to pass through the soil. Permeability of the soil sample was calculated using a model based on Darcy's Law. As part of the Quality Assurance Plan, all tests were run in triplicate for each soil type. Since the test apparatus operated under reasonably high gas pressure and the permeant (TCE) is a hazardous material, a Safety Plan was developed for the laboratory study. (Details of the plan are discussed in Section 6 of this report.)

The data obtained were analyzed to determine the effect of the TCE on the permeability of the three types of soils. The permeability test results with water showed that all three clay liners had low permeabilities ranging from 10^{-8} cm/sec to 10^{-9} cm/sec. In all cases good reproducibility in the data from triplicates was observed, indicating a reliable data base.

The results of the tests with TCE as the permeant show that the permeability is lower by approximately one order of magnitude than that with water. It was thought that the lateral pressure in the flexible wall permeameter may have contributed to the lower permeability. However, Phase 2 tests run at lower lateral pressures did not reveal a significant difference in soil permeabilities with the TCE permeant. Several factors can potentially be responsible for the apparent decrease in permeability when TCE is used. These factors are surface tension effects or partitioning effects and are discussed in Section 7 of this report.

This report incorporates the results of the laboratory investigation and presents the evaluation of the effectiveness of the clay liner materials investigated to contain TCE contaminated soils. In summary, the following conclusions were derived from this work:

(a) A significant decrease in clay soil permeability was observed with pure TCE as the permeant as compared to water.
(b) The decrease in permeability was observed for all three soil types when exposed to pure TCE as the permeant. All three test soil types experienced a similar amount of permeability decrease.
(c) Within a limited range, the lateral pressure within the test cell did not have a significant effect on the measured soil permeability.
(d) The permeability test results exhibited a high degree of consistency in results between the triplicate columns.
(e) The test apparatus and procedures used for the testing were found to be effective, reusable, and convenient for conducting these permeability investigations.

Two of the issues which remain unresolved are:

(a) Explaining the mechanism or cause for the lower soil permeability with pure TCE.
(b) The effect on soil permeability of less concentrated TCE permeants.

Additional testing and evaluation of these issues are recommended to provide input for determining the suitability of clay liners for containing TCE contaminated soils.

1. INTRODUCTION

1.1 Background. Contamination of soils and groundwater with trichloroethylene (TCE) has been found at various locations in and around the Sharpe Army Depot (SHAD), which is situated about three miles northwest of the Town of Lathrop, California in the San Joaquin Valley. The primary source of TCE contamination at SHAD is attributed to the past maintenance activities for Army aircraft, vehicles, and industrial and medical equipment. These past operations involved the use of solvents for vapor degreasing, paint stripping and spraying, metal dip cleaning, and metal plating.

USATHAMA is currently investigating several alternative methods for remedial action at TCE contaminated sites such as the Sharpe Army Depot. One option for remedial action is excavation and containment of contaminated soils in a clay-lined disposal area. A major advantage of this remedial method is the relative cost-effectiveness when compared to soil treatment, incineration, or off-site disposal.

A review of the technical literature shows that several studies have been conducted to determine the effects of organic solvents on clay liners. These studies are discussed in subsequent sections of this report. The effect of solvents on clay liners varies depending on the type of solvent, the nature of the clay liner, and other test conditions. However, specific literature concerning the application of clay liners to contain TCE-bearing wastes is very limited.

1.2 Objectives. The primary objective of this investigation was to determine the effectiveness of clay soils as liner material to contain TCE contaminated soils. This investigation was specifically designed to meet the following objectives:

(a) Identify the effect of TCE on the permeability of clay liners.
(b) Identify the effect of TCE on the structural integrity of clay liner materials.

1.3 Programmatic framework. This investigation was aimed at an evaluation of the applicability of clay liners to contain TCE contaminated soils. It is a part of the overall effort by USATHAMA to determine the most cost-effective, environmentally sound method for treatment and disposal of TCE contaminated soils. Other technologies for TCE treatment and disposal are under investigation, but discussion of such is beyond the scope of this report.

2. BACKGROUND INFORMATION

2.1 Previous studies. Before preparing the test plan for this laboratory investigation, a computerized literature search was conducted to identify previous and on-going research studies on the effects of hazardous materials (particularly organic solvents) on the performance of clay liners. As part of this literature search, information summarized in an earlier report prepared by WESTON (1) was reviewed. The available literature on the previous studies was reviewed, and the findings were discussed with researchers so that any additional up-to-date information could be obtained. Salient aspects of these studies are summarized in Table 1.

From the literature review it was determined that previous studies have addressed two major subject areas, as follows:

(a) Determining the effect of different organic chemicals on the permeability of clay soils.
(b) Characterizing the factors influencing the interaction of organic chemicals with clay liner material and their resultant effects on permeability.

Based on the literature, three types of clays are generally used in laboratory evaluations of clay liners. These include kaolinite, illite, and montmorillonite.

The type of permeability test apparatus (permeameter) used for the tests is either the rigid-wall type or the flexible-wall type. Schematics of the two types of permeameters are shown in Figure 1. In the rigid-wall type permeameter, the soil sample is contained in a metal cylinder and the permeant flows through the soil medium due to the hydraulic gradient created by the pressure differential applied to the top and bottom of the soil sample. In the flexible-wall type permeameter, the soil sample is encapsulated in a flexible membrane instead of a rigid cylinder. The encapsulated sample is enclosed in a cylinder filled with water. In addition to applying vertical pressures to the top and bottom of the soil sample, lateral pressure is applied using air or inert gas (usually nitrogen) into the water around the sample. The lateral pressure is applied to simulate the overburden pressure that normally exists under field conditions.

There is a basic difference in opinion among researchers regarding the preferred type of permeameter to be used for conducting the studies. Some researchers believe that the rigid-wall permeameter should be used due to its low cost, ease of operation, better control under test conditions, and applicability to compacted soils. Critics of this concept argue that there may be imperfect contact between the soil and the inside

TABLE 1. STUDIES ON HAZARDOUS MATERIAL/CLAY LINER COMPATIBILITY

Researcher(s)	Waste materials	Waste concentrations	Clay type(s)	Reference no.	Type of permeameter
Brown and Anderson	Acetic acid Aniline Methanol Acetone Ethylene glycol Heptane Xylene Water (0.02 N $CaSO_4$)	Pure	Noncalcareous smectite Calcareous smectite Mixed cation kaolinite Mixed cation illite	7, 16, 17	Rigid wall
Daniel and Foreman	Water Methanol Heptane	Pure	Noncalcareous smectite Mixed cation illite Commercially-processed kaolinite	6, 15	Rigid and flexible wall
Brown, Thomas, and Green	Water Water/acetone mixtures Acetone/xylene mixtures Diesel fuel Kerosene Gasoline Motor oil Paraffin oil		Sandy loam/kaolinite clay blend Sandy loam/mica clay blend Sandy loam/bentonite clay blend Commercial-blue bentonite clay Commercially-treated bentonite clay (Both above diluted with sand)	14, 18	Rigid wall
Peirce, et al.	Ferric chloride Nickel nitrate	Low (ppm)	"White store" clay (montmorillonitic) "Hoytville" clay (illitic) "Faceville" clay (illitic)	23	Flexible wall
Acar, Olivieri, and Field	Phenol Acetone Nitrobenzene Benzene	Pure	Kaolinite (commercial)	8, 10	Rigid and flexible wall
Kugelman, Fang, and Evans	Water Sodium hydroxide Hydrochloric acid Aniline Acetic acid Acetone Carbon tetrachloride	Varying	Kaolinitic soil Illitic soil Montmorillonitic soil	24	Rigid and flexible wall
Haxo	Nitric acid Hydrofluoric acid Acetic acid Caustic-brime solution Gasoline wastewater Aromatic oil Weed oil Weed killer	Varying	Modified bentonite and sand	20	Rigid wall

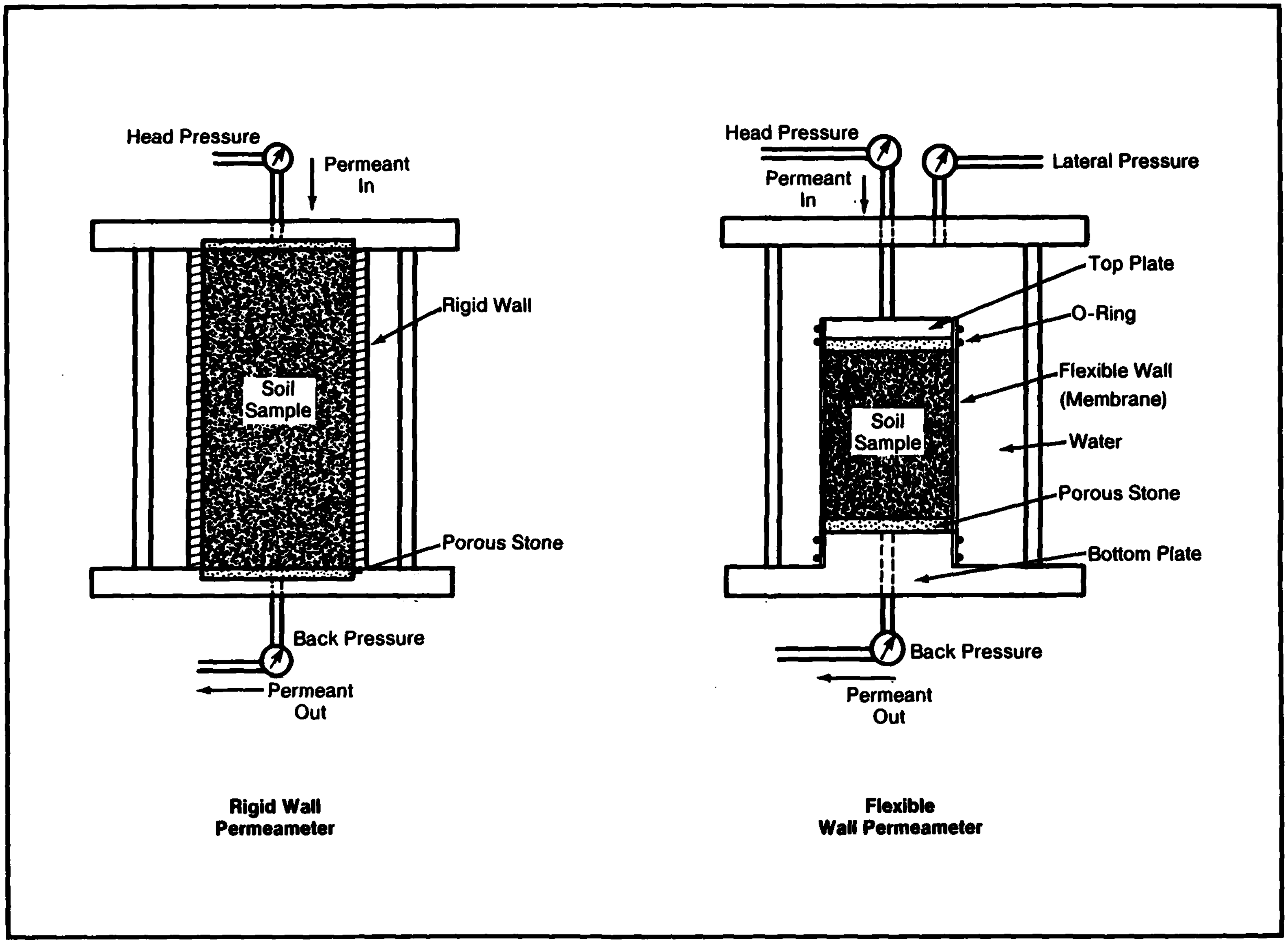


FIGURE 1 SCHEMATIC DIAGRAMS OF RIGID-WALL AND FLEXIBLE-WALL PERMEAMETERS

surface of the rigid-wall cell, which can lead to sidewall leakage and result in erroneously large permeability values. Sidewall leakage effects could be a critical factor when the permeants used are organic solvents. This is because organic solvents have a tendency to cause shrinkage of the soil, thereby creating a detachment of the soil column from the rigid wall of the cylinder and allowing permeant flow along the sidewall. It is hypothesized that the application of lateral pressure in flexible-wall permeameters not only prevents sidewall effects, but also better represents field conditions wherein overburden pressure is actually exerted on the soil column. The lateral pressure helps to seal the cracks formed by shrinkage of soil. In contrast to this hypothesis, proponents of the rigid-wall concept argue that, although the rigid-wall system may, in some cases, result in more-conservative values for permeability, tests performed with high lateral pressures (in flexible-wall permeameters) may not be realistic and could lead to an overestimation of the performance of the clay liner.

Comparative studies on the two types of permeameters have been conducted by Daniel (5), Foreman (6), and others. Tests have shown that the rigid-wall permeameters generally result in higher permeability measurements than the flexible-wall type in the case of organic solvents. However, tests conducted at hydraulic gradients greater than 100 ft/ft did not indicate significant differences in permeability between the two types of permeameters. Several factors may be responsible for the differences in results, and, at this point, the effect of the type of permeameter used is still not well understood. Based on a review of findings in the literature, it is difficult to recommend with certainty the type of permeameter suitable for a particular application, although it is generally believed that the flexible-wall type appears to be more suitable for tests with organic solvents.

Regarding the effect of organic solvents on the permeability of clay soils, the literature reveals a wide variety of findings. Although some data are available for certain permeants like methanol, acetone, heptane, and xylene, limited research has been conducted with trichloroethylene (TCE). In a majority of the studies, the soil sample is first subjected to water as the permeant up to about two pore volumes of liquid. The permeant under study is then added to the soil column. The water used for the initial portion of the tests is a salt solution of 0.01N calcium sulfate. The basis for using this particular type of water is not well documented. It is believed that it is used to simulate groundwater conditions with a given amount of hardness contributed by the divalent calcium present. Permeability investigations were conducted by Anderson, et al. on four types of clay soils (calcareous and noncalcareous smectite, kaolinite, and illite) subjected to water (0.01N $CaSO_4$), acetic acid (organic acid), aniline (organic base), three neutral polar organic compounds (ethylene glycol, acetone, and methanol), and two neutral nonpolar organic compounds (xylene and heptane). Permeability and breakthrough curves of the four clay soils treated with the organic solvents are shown in Figure 2 (7). Results of this study indicate the following:

(a) All four of the clay soils show permeabilities lower than 1×10^{-7} cm/sec when treated with water (0.01N $CaSO_4$). However, the same clays underwent large permeability increases (one or two orders of magnitude) when subjected to the organic fluids. Of the four clays, smectite (a form of montmorillonite) showed greater increases in permeability when exposed to the organic fluid.

(b) A significant amount of soil was observed in the effluent in the tests with acetic acid. This effect was caused by the dissolution of the soil particles by the acid. Massive change in the soil structure characterized by visible pores and cracks in the soil surface was the predominant effect resulting in increased permeability in the case of organic base (aniline) and the nonpolar and polar organic solvents.

The effect of organic fluids on permeability of compacted kaolinite was investigated by Acar, et al. using rigid-wall and flexible-wall permeameters (8). The permeation fluids were 0.1 percent and 100 percent solutions of nitrobenzene, acetone, phenol, and benzene. Large increases in permeability were observed in tests with rigid-wall permeameters; the increase was attributed to side wall leakage due to shrinkage of the soil. All tests with chemicals at low concentrations resulted in slight decreases of permeability. With pure solutions, the permeability slightly increased with acetone and phenol and significantly decreased with benzene and nitrobenzene. Diffusion through the cell membrane was found to be a considerable source of error in assessing the permeability with concentrated solutions of organic fluids.

Based on this study and other investigations by the same researcher, hydraulic conductivity with organic fluids was found to be dependent on the surface forces of interaction on clay particles and these forces affected the flow characteristics (9) (10) (11). Studies by other researchers such as Fang (12), Alther (13), and Green (14) also show results which indicate that tests using rigid-wall permeameters show higher permeabilities with organic solvents than with flexible wall permeameters, and organic solvents tend to cause shrinkage of clay liners. These two conclusions generally summarize the findings of past studies investigating the effects of organic fluids on clay liners.

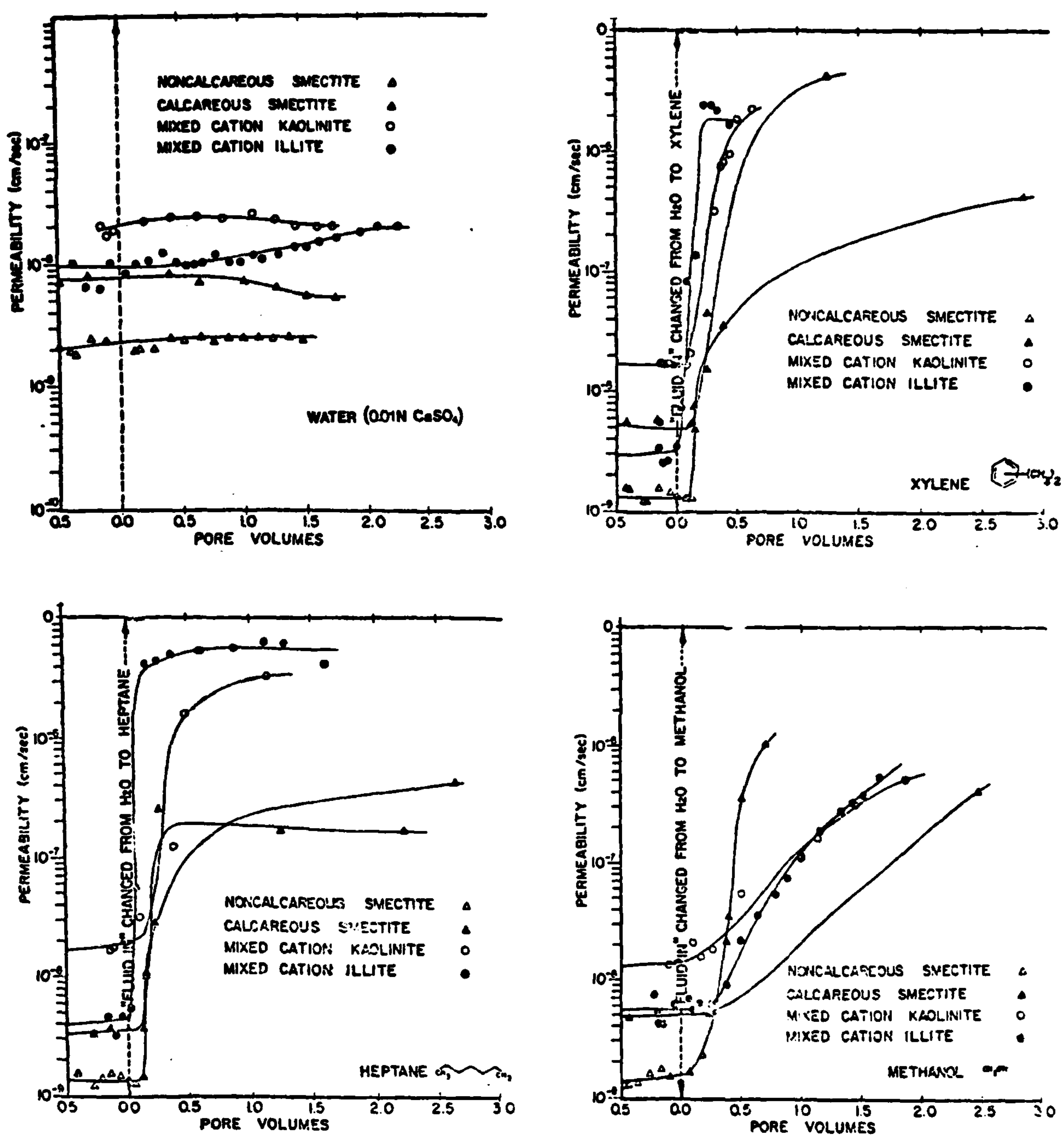


FIGURE 2 PERMEABILITY CURVES OF FOUR CLAY SOILS TREATED WITH WATER AND ORGANIC SOLVENTS (7)

Researchers have attempted to determine the causes of permeability increases in clays exposed to organic fluids. To this end, investigations have been conducted on the factors affecting the interaction of the organic compounds and the clay soils (15) (16) (17). Tables 2 and 3 summarize the properties of some clay soils and organic fluids which are used for most permeability studies.

One of the factors that affects permeability is the density-to-viscosity ratio of the permeant. In almost all cases, the increase in permeability observed was significantly higher (four to six times) than that projected based on comparative density-viscosity ratios between the permeant and water (18). The large increases in permeability in soils subjected to organic fluids thus could not be explained based only on the density-viscosity ratio concept.

According to studies by Green, et al., the hydrophobic nature of an organic fluid is more important than density or viscosity in predicting its permeation through clay soils (18). This is based on the concept that as molecules of the permeant move through the intersticial water column in the soil medium, the molecules are partitioned between the aqueous phase and the surrounding soil particles (by sorption). Hydrophobic substances, such as benzene, xylene, carbon tetrachloride, and trichloroethylene, are highly partitioned onto the soil phase and are expected to have permeabilities lower than that of water. Molecules weakly sorbed by the soil particles tend to move more quickly through the aqueous channels.

To exemplify this theory, a comparison was made between the octanol/water partition coefficients of different permeants and their permeabilities as presented in Table 4. The octanol/water partition coefficient is a measure of the tendency of permeant molecules to escape from the aqueous phase. From Table 4 it is seen that, in general, the permeability of a liquid decreases as the log of its octanol/water partition coefficient increases. In other words, as hypothesized earlier, the more hydrophobic the organic permeant, the lower the permeability.

In continuation of this theory, another parameter often used to compare hydrophobicity of liquids and their permeabilities is the dielectric constant. According to Green, there is a relationship between the dielectric constant and permeability of organic fluids (18). The greater the dielectric constant, the higher the permeability. Low dielectric substances will be sorbed more on the soil medium and thus have lower permeabilities.

TABLE 2. CHARACTERISTICS OF COMMONLY USED CLAY SOILS

Clay soil description	Noncalcareous smectite	Calcareous smectite	Mixed cation kaolinite	Mixed cation illite	Mica	Bentonite
Sand, percent (50 nm)	35 - 37	7 - 8	39 - 41	14 - 15	60.4	75.9
Silt, percent (50 - 2.0 nm)	26 - 28	42 - 44	17 - 18	38 - 39	17.6	3.9
Clay, percent (2.0 nm)	36 - 38	48 - 50	42	47	22.0	20.2
Predominant clay minerals*	1. Smectite 2. Mica 3. Kaolinite	1. Smectite 2. Kaolinite	1. Kaolinite 2. Mica	1. Illite 2. Smectite	1. Mica 2. Kaolinite 3. Montmorillonite	1. Bentonite 2. Mica (trace)
Shrink-swell potential	Very high	Very high	Moderate	Moderate	---	Very high
Corrosivity (steel)	High	High	High	---	---	---
Cation exchange (meq/100 gms)	24.2	36.8	8.6	18.3	7.3	18.9
Total alkalinity (meq/100 gms)	3.3	129.2	0.8	4.2	---	---

*In order of descending quantity in the soil.

TABLE 3. PHYSICAL AND CHEMICAL PROPERTIES OF COMMON ORGANIC FLUIDS

Permeant name	Water solubility (gm/L) at 20°C	Dielectric constant at 20°C	Dipole moment (debyes)	Temperature range of the liquid State (°C) freezing	boiling	Viscosity (centipoise) at 20°C	Density (g/cm³) at 20°C	Molecular weight
Acidic acid		6.1	1.74	17	118	1.28	1.05	60
Aniline	34.0	6.9	1.55	-6	184	4.40	1.02	93
Acetone		20.7	2.90	-95	56	0.33	0.79	58
Ethylene glycol		38.66	2.28	-13	198	21.0	1.11	62
Heptane	0.003	1.0	0.00	-91	98	0.41	0.68	100
Xylene	*0.20*	2.5	0.40	-47	137	0.81	0.87	106
Water		80.4	1.83	0	100	1.0	0.98	18
Methanol		31.2	1.66	-98	65	0.54	0.79	32
Glycerol	—	42.5	—	1.6	290	1,412	1.26	92
Trichloroethylene	1.1	3.4	0.80	-85	87	0.34	0.79	131
Carbon tetrachloride	—	2.2	0	-23	77	0.10	1.59	154
Benzene	1.8	2.28	0	6	80	0.65	0.88	78

TABLE 4. PERMEABILITIES AND OCTANOL/WATER PARTITION COEFFICIENTS FOR SOLVENTS ON THREE CLAY SOILS (18)

Clay soil	Solvent	Equilibrium coefficient of permeability ($\times 10^{-9}$ cm/sec)	Log octanol/water partition coefficient
Ranger shale	Benzene	2.0	2.13
	Xylene	4.0	3.15
	Carbon tetrachloride	25	2.64
	Trichloroethylene	2.0	2.37
	Acetone	2.5	-0.24
	Methanol	15	-0.32
	Glycerol	0.9	-2.56
	Water	38	-1.15
Kosse kaoline	Xylene	50	3.15
	Acetone	65	-0.24
	Water	220	-1.15
Fire clay	Xylene	1.0	3.15
	Carbon tetrachloride	2.5	2.64
	Acetone	7.0	-0.24
	Water	13.5	-1.15

In contrast to the projected permeability patterns based on the above discussed theory, anamalous behavior was observed with some organic solvents. For example, carbon tetrachloride demonstrated a significantly higher permeability when compared with other solvents like acetone and methanol having similar dielectric constants and octanol/water partition coefficients (18). In such cases, a breakthrough phenomenon in the permeant/soil matrix occurs due to shrinkage of the soil medium. Shrinkage causes the soil medium to pull away from the surrounding surface and also produces cracks within the soil medium; thus, channels are formed in the soil through which the solvent flows easily, indicated by a sudden increase in permeability.

Based on this literature review of previous and on-going studies on clay-liner performance, the following conclusions were made:

(a) A controversy in the research community appears to exist regarding the suitability of rigid-wall or flexible-wall test methods for permeability studies on clay liners. It appears, however, that the flexible-wall method may be more applicable for tests runs using organic solvents as the permeant.
(b) A standardized procedure for conducting permeability studies on the effect of organic solvents/hazardous wastes on clay soils is not well established; therefore, a direct comparison of the results of different studies is difficult.
(c) Studies conducted to date by different researchers on various clays and organic solvents indicate a wide range of findings.
(d) Studies indicate that organic solvents generally tend to cause shrinkage and cracks in the clay soil material, resulting in breakthrough effects as measured by sudden large increases in permeability.
(e) Uncertainties exist as to what solvents produce breakthrough effects in which types of soil. Further unknowns relate to effects of permeant concentration, long-term stability, and other factors on breakthrough phenomenon.
(f) Existing test or research information related to the effect of TCE on clay soils is scarce.

From this literature review, it was found that adequate information is not yet available to determine the suitability of a clay liner for a given solvent based on published information. Actual test or research studies on the effects of TCE on clay soils have been minimal. Site-specific bench-scale studies are considered essential to determine the suitability of clay soils for containing TCE contaminated soils.

2.2 Soil characteristics. The following investigation to evaluate effects of TCE on clay soils was designed to generate data for clay types local to the area around the Sharpe Army Depot (SHAD) in Lathrop, California. The investigation included the evaluation of three alternative soil types as clay liners for containing TCE contaminated materials. Characterization of each of these soils was necessary as a part of the evaluation process.

The first type of soil evaluated was a local clay that could be used as liner material or for capping purposes in landfills. A borrow pit site was located in Tracy, California, which is about 15 miles from the SHAD site. Given the low permeability of the clay and its proximity to the SHAD site, it was considered as one of the alternative types of clay to be evaluated in this study.

The second type of soil considered was the local soil in and around SHAD. Information was obtained from the USDA Soil Conservation Service in Stockton, California regarding the characteristics of the local soils. The soil in the area is generally classified as a loamy sandy soil with moderate permeability. However, it is also noted that there is a considerable variation in the type of soil in the area around SHAD. Although the local soil is not a clay and hence cannot be a candidate liner by itself, a mixture of the local soil with a commercially-processed clay was used as a candidate liner material for this investigation. (Commercially-processed clays are generally modified forms of natural bentonite clay. These are used as an admixture with native soil to form a soil liner material.)

The admixture selected is Volclay (Type SS-100) manufactured by the American Colloid Company, Skokie, Illinois. The Type SS-100, known as "Saline Seal," was recommended by the manufacturer for this particular application.

The SS-100 Volclay is a specially treated high swelling sodium bentonite. When wetted, the Volclay expands due to its unique molecular structure. The presence of sodium ions allows Volclay to swell to a much greater volume than other types of bentonite. The American Colloid Company's treatment of the sodium bentonite is specially designed to incorporate chemical resistant properties. The resultant SS-100 Volclay-soil mix should produce a highly resistant liner material capable of containing high concentrations of hazardous materials without significant degradation.

The rate of application of the Volclay to the local soil sample was recommended by the vendor based on their laboratory tests conducted on a soil sample. The local soil and Volclay mix was composed of 6-percent Volclay and 94-percent soil. The amount of Volclay added to the local soil was determined based upon the dry weight of the local soil. Information provided by the vendor on the application and use of Volclay is presented in Appendix A.

The third type of clay considered as a liner alternative was kaolinite. Kaolinite is a type of natural clay; however, it is not found local to the SHAD area. It is one of the common types of clays considered for use as a liner material for containing contaminated/waste materials. Kaolinite (Hydrite R type) was purchased from a vendor (Georgia Kaolin Company, Elizabeth, New Jersey).

Illite, which is another type of clay, was not selected as one of the alternative soil types because past studies indicate that it generally undergoes significant increases in permeability when subjected to organic solvents. The other common type of clay often considered for evaluation as a liner material is montmorillonite. Based on a review of research studies, it is believed that naturally found montmorillonite generally tends to undergo an increase in permeability under the action of organic solvents; therefore, naturally found montmorillonite was not selected as a candidate alternative type of liner material for evaluation in this study.

3. PARAMETERS AND TEST CONDITIONS

3.1 Test parameters. Fourteen experimental variables were identified as having relevance to this study. Table 5 summarizes these parameters in terms of incorporation into the bench-scale investigations. Control variables are those variables that are controlled during testing. Specified or response variables are values determined as a function of the testing operations. The three control variables were pressures exerted on the liner material to simulate field conditions. Seven of the specified or response variables were related to the soil characteristics of the liner materials. The remaining specified or response variables were associated with resultant measured values during testing. All of the experimental variables were measured values.

3.2 Test conditions. The test conditions included three major considerations for conducting the bench-scale investigation. These considerations were:

(a) Type of permeameter (rigid-wall or flexible-wall).
(b) Concentration of TCE.
(c) Type of soil.

Based on review of previous studies and engineering judgment, the flexible-wall type permeameter was considered to be more appropriate for conducting this evaluation of clay liners subjected to TCE. The key consideration governing this decision was to avoid/minimize the potential problem of the permeant (TCE) flowing in bulk along the sidewall of the permeameter due to shrinkage of the clay soil material. Such bulk flow of the permeant would result in a sudden apparent increase in permeability which is erroneous. This problem has been reported by other researchers in previous studies conducted with rigid-wall permeameters.

The second test condition related to the concentration of TCE to be used for conducting the permeability tests. Following discussions with USATHAMA, the decision was made to perform the tests with a commercial-grade concentrated TCE solution (~ 100 percent TCE concentration). The 100-percent TCE concentration was considered to be the "worst case" condition. Considering the possibility of modifying this test condition during the investigation, a contingency plan was developed (Subsection 6.5).

TABLE 5. ANALYSIS OF EXPERIMENTAL VARIABLES

Parameter, variable or characteristic	Control variable	Specified or response variable	Sample type discrete	Sample type continuous
Liquid limit, soil		X	X	
Plastic limit, soil		X	X	
Plasticity index, soil		X	X	
Optimum soil moisture content		X	X	
Soil density		X	X	
Void ratio		X	X	
Particle size distribution, soil		X	X	
Volume of water (0.01N $CaSO_4$) permeated		X		X
Volume of TCE (permeated)		X		X
Time of permeation of water		X		X
Time of permeation of TCE		X		X
Head pressure	X			X
Back pressure	X			X
Lateral pressure	X			X

The third test condition concerned the types of soil to be evaluated as liner material. Three types of soils were used for test purposes:

(a) Locally available native clay.
(b) Locally available native soil mixed with a commercially available clay admixture.
(c) Kaolinite; natural clay, not locally available.

The basis for selection of the locally available types of test soils was to minimize the cost of purchasing and transporting clay from external sources should the local soil prove not suitable for this application. Kaolinite was selected as the third test soil type for purposes of evaluating a commercially available clay as a potential liner material.

4. TEST APPARATUS

4.1 Background. Careful consideration was given to determine the most appropriate type of flexible-wall test apparatus for the bench-scale study. This was particularly important because no standard laboratory equipment or procedure exists for conducting permeability tests on clay liners using a flexible-wall type permeameter. A review of the literature and discussions with researchers helped to identify the problems experienced with fabrication of the test apparatus, as well as operation of the equipment.

The test apparatus used for this study was based on equipment developed at Duke University by Peirce, et al. (2, 23). It has been successfully used for conducting similar studies with different types of organic solvents. The test apparatus was a modification of the conventional equipment used for conducting triaxial tests on soils. A schematic of the test apparatus is shown in Figure 3.

Considerations for selection, design, configuration, and operation of the bench-scale apparatus included the following:

(a) The first consideration for simulating the field conditions was to provide a flexible-wall type system to enclose the soil samples. A flexible inner membrane made of Teflon was used for this purpose. The Teflon inner membrane was held in place by an outer latex membrane wrapped around it. Teflon was selected as the inner membrane because of its higher resistance to possible attack or damage from the TCE permeant.

(b) In the test permeameter, head pressure was applied on the sample from the top; back pressure was applied from the bottom of the sample. Because it was a flexible-wall system, lateral forces had to be applied to the permeameter to simulate the soil overburden pressure. This was accomplished by means of a pressurized water jacket around the latex membrane. The water jacket was pressurized using a lateral pressure cell. The lateral pressure cell was a pressurized water reservoir that applied the lateral pressure to the permeameters. The pressure was applied using nitrogen gas. The head pressure moved the liquid (permeant) through the permeameter. The back pressure ensured that the entrapped air in the sample was eliminated, since entrapped air can result in low coefficients of permeability (3). A positive head differential was maintained across the permeameter. Permeation of the

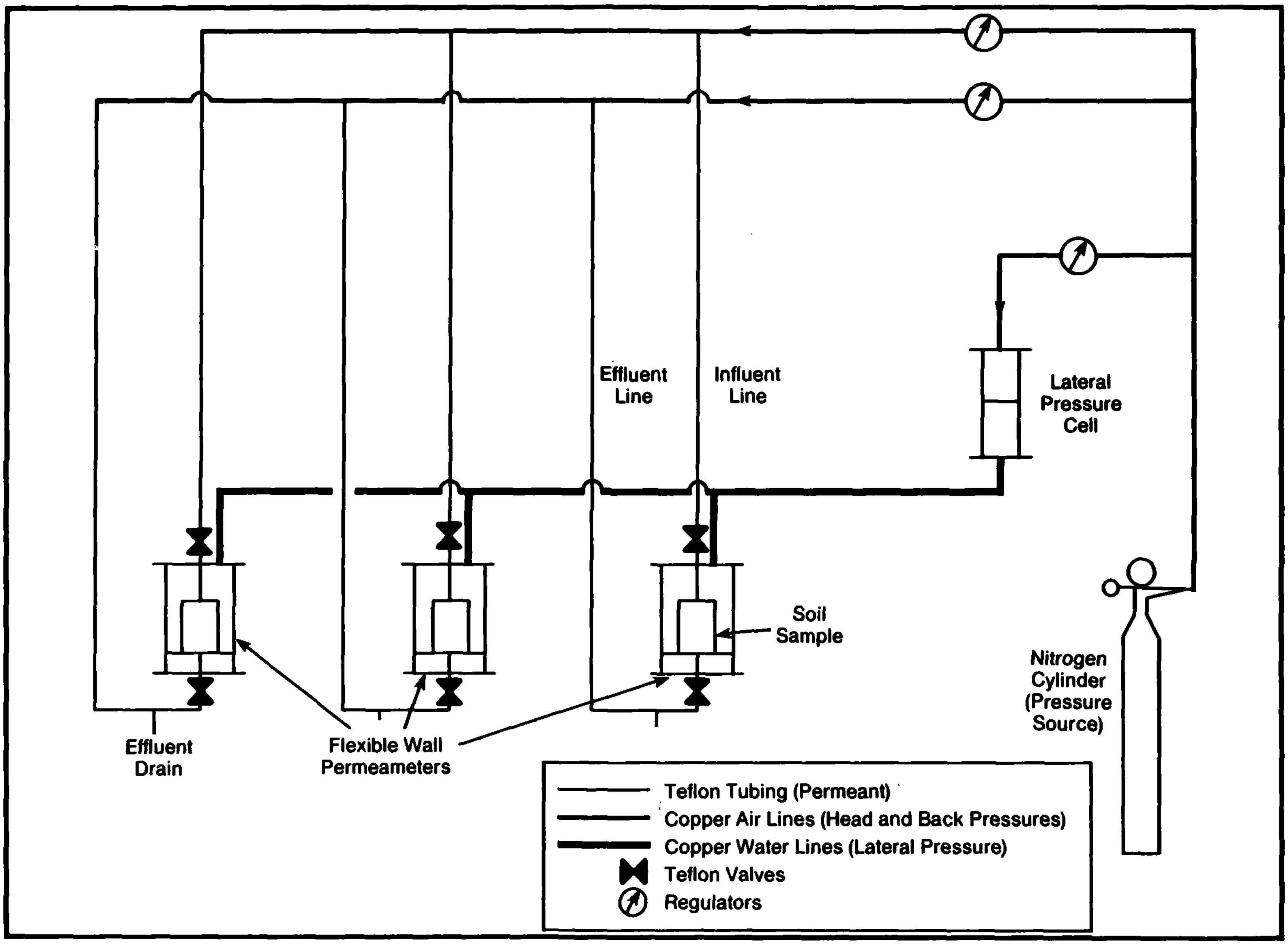


FIGURE 3 SCHEMATIC OF CLAY LINER PERMEABILITY TEST APPARATUS

solvent (TCE) was induced in response to the hydraulic gradient. By regulating the three pressures, it was possible to simulate the in situ soil state of stress, as well as develop appropriate gradients to establish measurable test times and/or simulate field conditions.

(c) An important consideration for the test system was the choice of gas used for applying pressure. Air or nitrogen can be used; however, nitrogen is recommended because it is an inert gas which precludes the potential for reaction of the permeant (TCE) or organics in the soil with the oxygen if air is used.

4.2 Test apparatus. The flexible-wall permeameter used for the bench-scale study is illustrated in Figure 4. A photograph of the test apparatus is shown in Figure 5. The soil sample (2.8 inches in diameter and 2 inches high) located inside the test cell was surrounded by a Teflon membrane. The membrane functioned as the flexible wall of the soil sample. Since the Teflon membrane may not have been capable of withstanding the lateral pressure applied to the sample, a latex membrane was placed around the Teflon membrane to provide additional strength. The latex membrane was retained around the Teflon membrane utilizing O-rings.

Porous stone plates were placed on the top and bottom of the sample. The purpose of the porous plate on the top was to uniformly distribute the permeant over the surface area of the soil sample. The porous stone plate at the bottom allowed the permeant to be collected from the entire cross-sectional area of the sample. Threaded Teflon caps were placed over the top stone plate and under the bottom stone plate and sealed with O-rings to apply the head and maintain back pressures.

The head pressure was applied through tube A (see Figure 4), and the back pressure was applied through tube C. A graduated stand-pipe was connected to tube A. The stand-pipe was filled with the permeant and was applied to the sample via the porous stone, utilizing tube A. The membrane-enclosed sample was housed in a plexiglass cylindrical chamber fitted with top and bottom plates. The chamber was filled with water, and the lateral pressure was applied to the sample by nitrogen gas through tube B. Pressure measurement gauges were attached to each of the pressure tubings. All tubings were 3/16 in. I.D. and were made of Teflon for the influent and effluent lines. Other tubings were of copper.

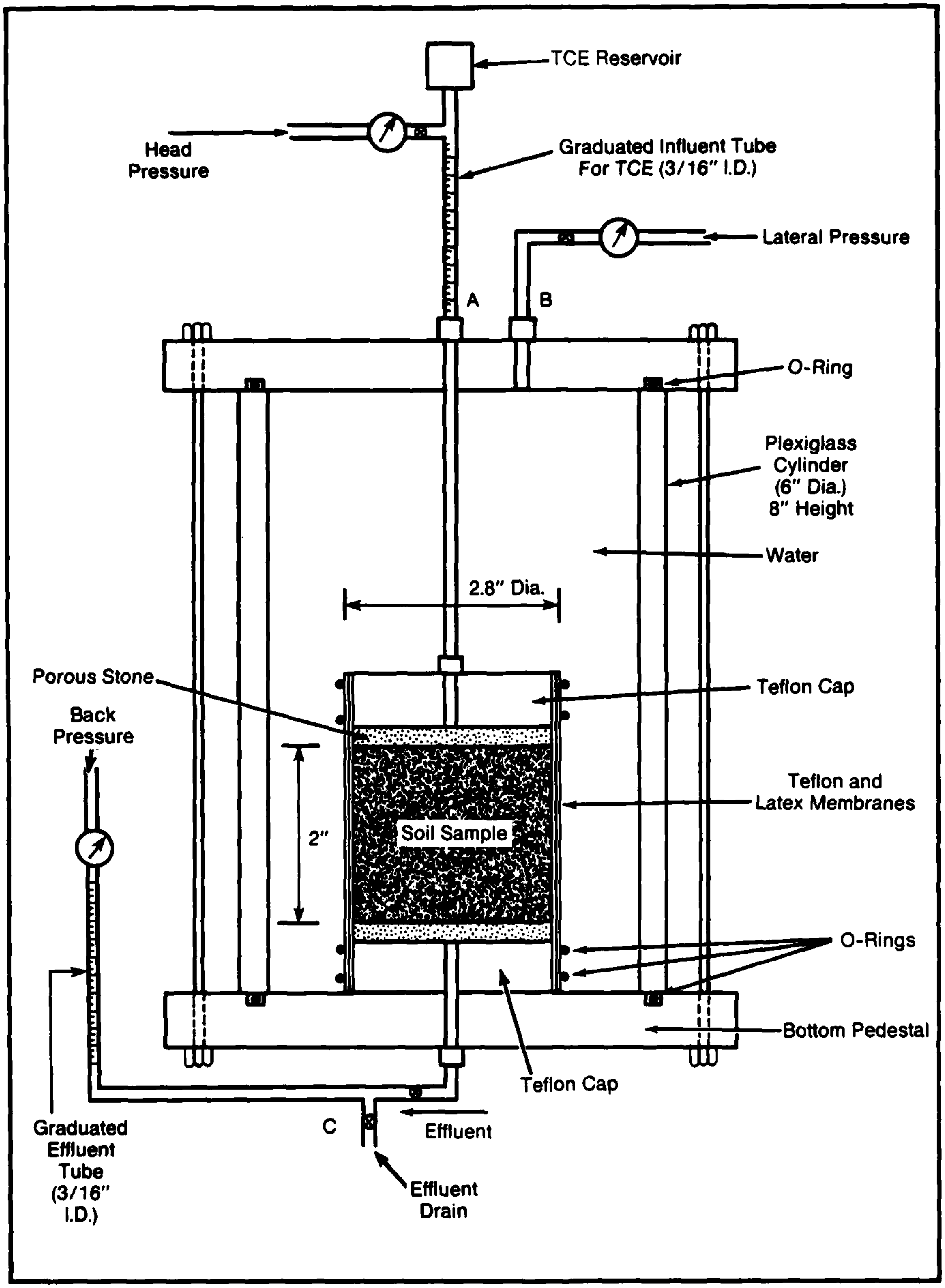


FIGURE 4 CLAY LINER PERMEABILITY TEST APPARATUS (FLEXIBLE WALL PERMEAMETER)

WESTON

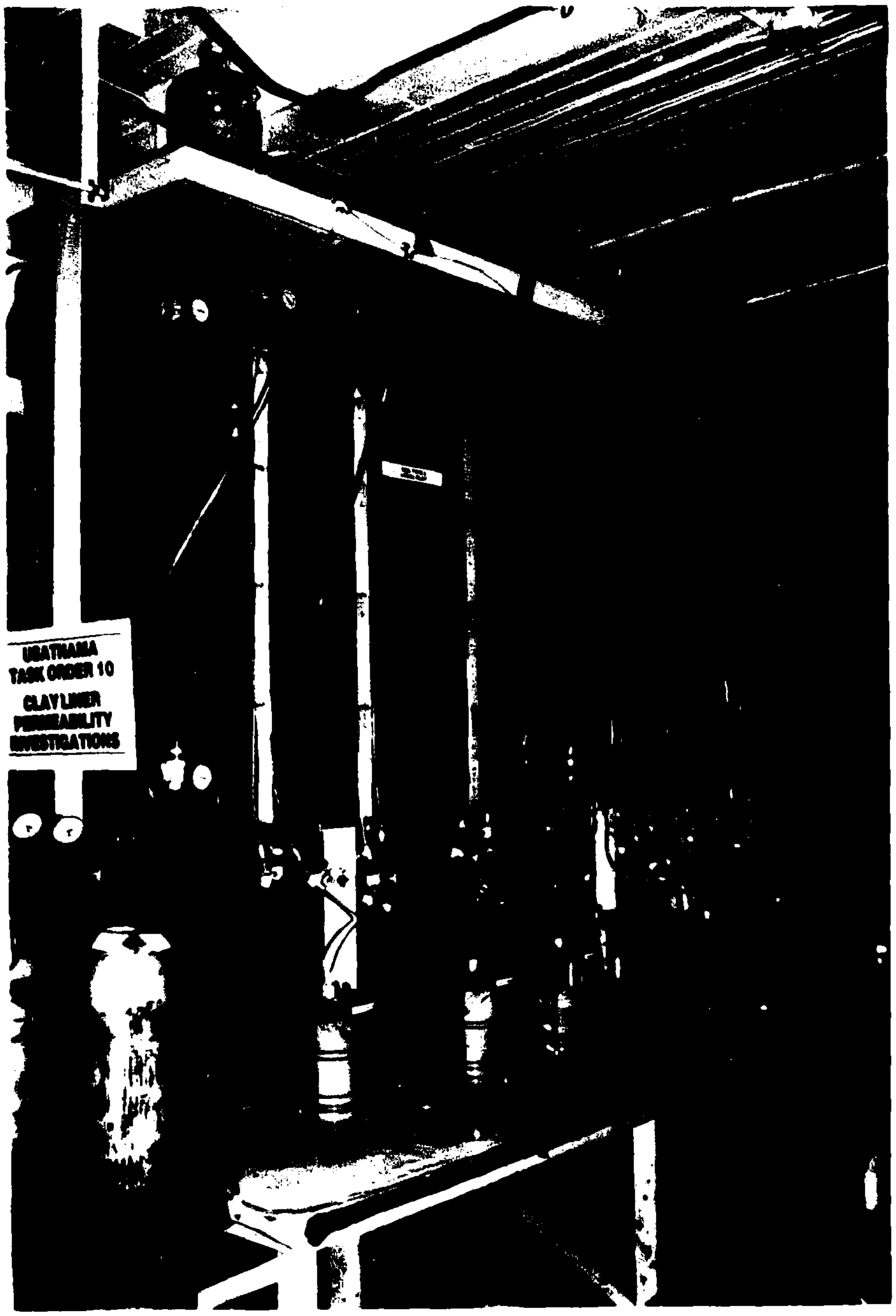


FIGURE 5 TEST APPARATUS FOR CLAY LINER PERMEABILITY STUDIES

5. SAMPLING AND ANALYSIS

5.1 Soil sampling. The bench-scale study was conducted with three soil types. The first soil type was the local clay which could be considered for use as liner or capping material in landfills in the area around SHAD. Based on WESTON's investigations, a local clay source was located in Tracy, California, which is about 15 miles from SHAD. Bulk quantities of the clay were obtained from the site and sent to WESTON's process development laboratory in West Chester, Pennsylvania. The test sample was prepared from this clay by WESTON per the procedure described later in this report.

The second type of soil evaluated consisted of a mixture of local soil and a commercially-available clay admixture. In general, the admixtures available in the market are modified forms of natural bentonite clay. For the purposes of this study, Volclay (Type SS-100), manufactured by American Colloid Company, was selected as the admixture for the local soil. The Volclay was mixed with the local soil based on the manufacturer's recommendations.

The third type of soil evaluated was commercially-processed kaolinite. The kaolinite was purchased from Georgia Kaolin Company, Elizabeth, New Jersey.

5.2 Soil characteristics. The three types of soil samples were analyzed for physical characteristics (particle size analysis, Atterberg limits, porosity, dry density, optimum moisture content using the moisture-density test, and specific gravity) and mineralogical classification using X-ray diffraction technique. The analyses were conducted by Valley Forge Laboratories, Inc., Devon, Pennsylvania. The results of the analysis are presented in Table 7. From the table it is seen that the local clay and the kaolinite contained a very high percent of fines. The plasticity of these two clays was also higher than that of the soil and Volclay mixture. The porosity of the kaolinite was relatively high compared to the others. One reason for the high porosity of the kaolinite is that it is a commercially-prepared clay of one particular size and does not have a gradation of different particle sizes like the naturally occurring other two types of soils. Mineralogical analysis of the soils showed that both the local clay and soil-Volclay mixture contained high percentages (50 to 65 percent) of quartz. Montmorillonite was below detection limits in the three soil samples.

TABLE 6. SOIL CHARACTERISTICS

Parameter	Local clay[1]	Soil and Volclay[2]	Kaolinite[3]
1. <u>Particle size analysis</u>			
% passing sieve 10	100	100	100
% passing sieve 40	98.2	87.6	100
% passing sieve 100	95.7	45.3	100
% passing sieve 200	93.5	36.8	99.2
2. <u>Atterberg limits</u>			
Plastic limit	27	17	26
Liquid limit	70	24	57
Plasticity index	43	7	31
3. <u>Porosity</u>	0.36	0.23	0.49
4. <u>Moisture</u>			
Maximum dry density (lb/cu ft)	98.2	126.5	106.7
Optimum moisture content (%)	18.8	11.4	19.3
5. <u>Specific gravity</u>	2.65	2.60	2.61
6. <u>Mineralogy</u> (%)			
Quartz	50	65	<1
Calcite	29	<1	<1
Albite	11	31	<1
Kaolinite	3	2	100
Illite	2	2	<1
Montmorillonite	<1	<1	<1

[1]Local clay - locally available clay near the SHAD site.
[2]Soil and Volclay - mixture of the local soil around the SHAD area and a commercially available admixture.
[3]Kaolnite - commercially available Kaolnite.

5.3 Soil preparation and handling. The soil sample used for the bench-scale permeameter test was prepared utilizing a series of steps as follows:

(a) Water (0.01N $CaSO_4$) was gradually added to about 500 g of the soil and hand mixed until the approximate moisture content required was reached. The desired moisture content was about 1 to 3 percent above the optimum content (defined by ASTM D-698-78 based on moisture-density relationships for each clay).
(b) The sample was sifted through a No. 4 sieve and stored in a sealed bag in a cool area overnight. This was to permit the sample to equilibrate as per procedures specified in ASTM D-698-78.
(c) The soil sample was compacted in a mold 2.8 inches in diameter as per the Standard Proctor Method (ASTM D-698-78). The depth of the compacted sample was 2 inches. It was compacted in two layers, each 1-inch thick.
(d) The sample was taken out of the compaction mold and weighed, and the bulk density was determined. A separate sample of soil prepared in a similar procedure was used for moisture content analysis. The sample was now ready for conducting the test in the flexible-wall permeameter.

5.4 Permeant. The permeants used for conducting the permeability studies were water and TCE. For purposes of this investigation, the water used was a 0.01N $CaSO_4$ distilled water solution. The $CaSO_4$ was added to distilled water to simulate the divalent calcium hardness often present in groundwater. $CaSO_4$ has been used by other researchers as a representative permeant for permeability testing. The second type of permeant used was commercial grade TCE purchased from a vendor supplying industrial chemicals.

6. EXPERIMENTAL PROTOCOL

6.1 Background. The objective of the experimental protocol was to design a test procedure to maximize the amount of information obtained with the limited number of experiments. The bench-scale study was conducted under the following test conditions:

(a) Three types of soils.
(b) 0.01N $CaSO_4$ distilled water solution.
(c) One concentration of TCE which was a pure TCE solution. The TCE used was of a commercial grade that is commonly available.
(d) Two lateral pressure conditions.

For each type of soil, the permeability tests were run in triplicate; that is, three test permeameters were operated simultaneously. The permeability test using TCE was preceded by performing a similar test with 0.01N $CaSO_4$ distilled water solution. The purpose of the water permeability test was to determine the intrinsic permeability of the clays with simulated groundwater. The results of this test were compared with the subsequent tests with TCE. Tests were conducted at two different lateral pressures.

6.2 Test procedure. The test procedure was a series of steps performed in a given order that were closely followed to ensure correctness and accuracy of results. For ease of understanding, the test procedure was divided into the following steps.

6.2.1 Sample mounting. The mounting of the soil sample in the permeameter was as follows:

(a) The influent and effluent lines used for supplying and collecting the permeant were flushed with deaerated water.
(b) A porous stone plate was placed on the bottom Teflon cap. A 2.8-inch diameter Whatman 1 filter paper wetted with deaerated distilled water was set on the porous stone plate.
(c) The soil sample was placed on the filter paper.
(d) A second wetted filter paper was placed on top of the soil sample and a porous stone plate set on the filter paper.
(e) The top Teflon cap was then placed on the porous stone plate and both Teflon caps greased with high vacuum silicon grease.

(f) The Teflon membrane was applied to the soil sample, porous stone plates, and Teflon caps. Teflon tape (6 inches wide) was used as the membrane. The tape was applied directly to the soil sample, porous stone plates, and Teflon caps. Care was exercised to avoid any wrinkles in the membrane. A plastic film (parafilm) was tightly applied to the Teflon membrane to help seal the Teflon membrane to the soil sample, porous stone plates, and Teflon caps.

(g) The latex membrane was mounted inside a 3-inch diameter hollow metal cylinder (membrane mounting jacket) and a slight vacuum applied to hold the membrane tight against the cylinder wall. The mounting jacket with the latex membrane was lowered onto the soil sample and the vacuum released attaching the latex membrane to the Teflon membrane. The latex membrane was then wrapped tightly around the Teflon membrane and the mounting jacket removed. O-rings were fitted on the top and bottom Teflon caps to hold the membranes together.

(h) The wrapped soil sample was then mounted into the permeameter. The latex membrane was fitted onto the bottom pedestal of the permeameter and secured with an O-ring. The influent and effluent lines were then secured to the Teflon caps.

6.2.2 Assembly of the permeameter. Assembly of the permeameter was as follows:

(a) The plexiglass cylinder (6 inches in diameter x 8 inches high) was placed in grooves on the bottom pedestal to enclose the sample. The cylinder sat securely on the bottom O-ring.

(b) The quick-connect pieces on the top plate of the cylinder and the one on the sample assembly were connected. The cell assembly was completed with the top plate placed in position and the screws tightened.

6.2.3 Sample saturation. The following steps were taken to ensure complete saturation of the sample prior to conducting the permeability tests:

(a) The test permeameter was filled with deaerated distilled water making sure that all air bubbles were removed from the permeameter.

(b) The inlet tubing on the top of the permeameter was immersed in a container of 0.01N $CaSO_4$ distilled water solution. A vacuum of 3 to 5 psig was applied (using a vacuum pump) to the bottom of the sample for approximately 8 hours.

(c) The vacuum was then released and the influent graduated tube was filled with 0.01N $CaSO_4$.

(d) The pressure regulators were adjusted to the following pressures:

	Phase 1 investigation	Phase 2 investigation
Head water pressure	50 psig	40 psig
Back water pressure	35 psig	30 psig
Lateral pressure	60 psig	45 psig

The head and back pressures were selected (based on previous research) to provide an adequate hydraulic gradient for permeant flow within a reasonable time period. The hydraulic gradient of 200 ft/ft is commonly used by investigations for similar permeability studies with clays. Past studies have shown that hydraulic gradients between 150 to 250 ft/ft do not significantly affect the permeability (15). The lateral pressure was selected to simulate a 20-foot saturated overburden condition. The height of the overburden was selected arbitrarily in conjunction with USATHAMA since a definite height of the landfill could not be projected at this time.

The pressures were gradually raised to the specified levels to avoid a sudden application of the pressure on the sample. The assembly was allowed to operate under this condition for 24 hours. Care was taken to ensure that the influent standpipe was filled with permeant (0.01N $CaSO_4$) at all times. At the end of 24 hours, the sample saturation was completed. The application of back pressure was important to ensure that air bubbles were removed from the system. The soil sample was then ready for conducting the permeability test.

6.2.4 Permeability test. The permeability test was conducted as follows:

(a) For the tests, the lateral pressure, the head pressure, and the back pressure were maintained at specified levels as presented above. The pressures were checked daily using a precision manometer; the pressures were then readjusted, if necessary.

b) The liquid level in the graduated influent and effluent lines were noted at regular intervals of about 2 hours for the first 12 hours. Readings were taken every 12 hours for the remaining period of the test. The influent column was refilled when the level became low.

6.2.5 Calculation of permeability. The permeability of the soil sample for a given permeant can be computed based on either the constant head test method or the falling head test method. In the test procedure described earlier, the constant head test condition was closely simulated. This was because the change in head column was expected to be only about 0.5 percent under the gradient applied (~200 ft/ft) for the 2-inch depth of sample. The permeability was calculated using the following model based on Darcy's Law (23):

$$K = \left[\frac{a \cdot L}{A \cdot t}\left(\ln\left[\frac{H_1 + H_3 + P_A - P_B}{H_2 + H_3 + P_A - P_B}\right]\right)\right]$$

where:
- a = cross-sectional area of columns (cm^2)
- A = cross-sectional area of soil sample (cm^2)
- t = time between two readings (sec)
- P_A = head pressure at influent column (cm of H_2O)
- P_B = back pressure at effluent column (cm of H_2O)
- H_1, H_2, H_3 = distances defined in Figure 6 (cm)
- L = height of soil sample (cm)
- K = permeability ($cm\text{-}sec^{-1}$)

6.2.6 Termination criteria for the permeability tests. It was difficult to establish a set criteria to determine when the test should be terminated. The different factors that dictated the termination condition were as follows:

(a) Sudden large increase of permeability (greater than three orders of magnitude), indicating breakthrough conditions or failure of the soil medium.
(b) Attainment of steady-state condition with respect to permeability.
(c) Passage of a sufficient number of pore volumes of permeant.

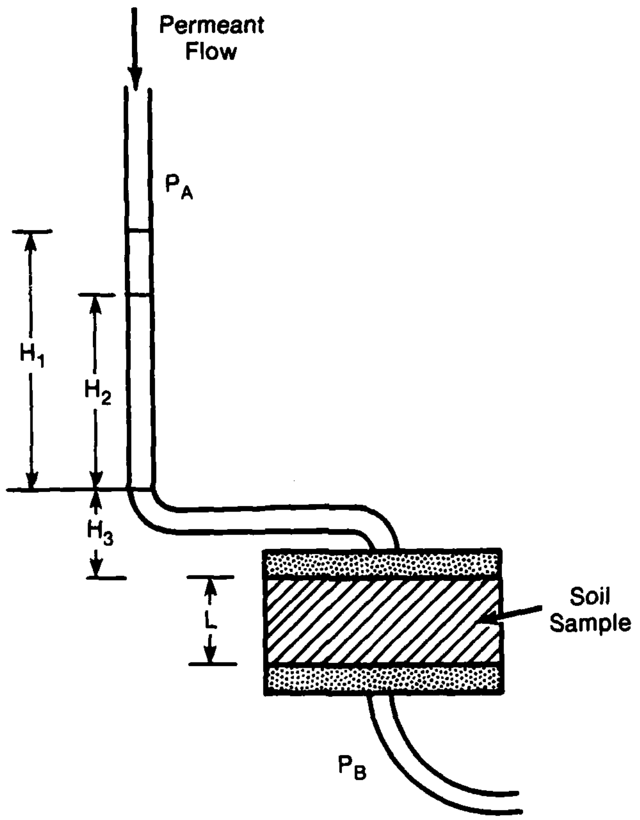


FIGURE 6 PARAMETERS USED FOR CALCULATING PERMEABILITY

The first condition is unique and, if it occurs, the test is automatically terminated. During the tests, such a condition was not observed. The second and third conditions were considered when determining the time for termination of the experiment. In order to determine if steady-state conditions had been obtained, permeability was computed for each time interval recorded. A linear regression analysis was performed to determine the slope of the permeability versus time curve. Initially, the slope may be large, but gradually it approaches zero as a steady-state condition is achieved. When the steady-state condition was reached the test was continued until approximately one to two total pore volumes of permeant passed through the sample. In some cases where the permeability was very low, it was difficult to permeate one or two pore volumes through the soil within a reasonable time period. In these cases, the test was run up to a maximum period of 30 days and, if permeability equilibrium was reached in that period, the test was terminated.

These termination criteria were based on the results of successful permeability studies using similar criteria by Peirce and Monserrate (4, 22).

6.3 <u>Quality assurance</u>. The experimental protocol was designed to ensure adequate quality assurance for the data generated. The following procedures were incorporated in the investigation as part of the quality assurance plan:

(a) All permeability tests were run in triplicate.
(b) The pressure on each of the lines (head pressure, back pressure, and lateral pressure) were checked daily and calibrated daily using a precision manometer.
(c) The test apparatus was pressure tested initially with water at pressures higher than test pressures to identify any leaks in the system. The system was made leak-proof before conducting the permeability tests.
(d) Nitrogen gas was used to apply pressures on the sample. Nitrogen was selected to eliminate the potential of any reaction of the TCE or organics present in the soil with oxygen if air was used.
(e) The water level in the lateral pressure cell through which the lateral pressure was applied was monitored. Any decrease in the water level was noted since it could indicate an infiltration of water from the test cylinder to the sample caused by cracks or rupture of the membrane. The membrane was visually inspected to identify any signs of failure.

(f) The liquid level in the graduated influent tube was noted at regular time intervals. As the TCE permeates through the soil sample, the liquid level should decrease; any rise in the liquid level was noted, and the test apparatus was checked for malfunction.

(g) The soil sample was visually observed to note any changes in its size or shape during experimentation. The observations provided additional information to explain the permeability data.

It is believed that, with the quality assurance procedures outlined above, it was possible to maintain adequate control on the experimental system and generate reliable data for the study.

6.4 Safety plan. It was recognized that the bench-scale study entailed the operation of a pressurized system and the use of a hazardous material which was highly volatile, namely trichloroethylene (TCE). A plan was developed to safeguard the health and safety of the personnel operating the system and to prevent potential damage to other facilities in the laboratory in case of an accident. The features of the Safety Plan were as follows:

(a) Operating personnel wore safety glasses, and/or face shields, butyl rubber gloves, and Tyvek aprons. This was necessary to avoid possible skin contact with the TCE.

(b) For pressure testing of the system, the test permeameter was filled with water and the nitrogen pressure applied. The use of water for the test was a safety feature since water leaks could be easily located in advance of ultimate bursting of the system. Use of pressurized air was considered dangerous since a sudden explosion may have occurred (which could not be anticipated) causing damage and injuries. The test apparatus was tested for pressure up to 100 psi, which was much higher than the normal range of pressures used for the experiments.

(c) The head pressure on the sample was applied using nitrogen gas through the influent tube containing TCE. A positive pressure was therefore maintained in the TCE column, and TCE vapor could not escape into the air around the test apparatus.

6.5 <u>Contingency plan</u>. The investigation was designed to evaluate the effectiveness of clay liners impacted by a pure TCE solution at 100 percent concentration. The reason for this selection was to generate information for a possible "worst-case" condition. However, there was some concern when the Test Plan was prepared that, at this very high concentration, TCE may cause massive changes in the structural integrity of the clay sample, resulting in failure of the liner in a very short period of time. In view of these considerations, a contingency plan was developed to modify the bench-scale investigations if significant breakthrough occured rapidly. For this investigation, the criteria to adopt the contingency plan was the increase of permeability by three or more orders of magnitude using TCE compared to that measured for the water (0.01N $CaSO_4$). Under field conditions, TCE concentrations in contaminated soil were anticipated to be much lower than 100 percent concentration and closer to the water solubility limits of TCE (1,100 mg/L).

In the proposed contingency plan, the permeability tests were to be conducted using a solution of water (0.01N $CaSO_4$) containing a TCE concentration of 1,100 mg/L. The types of soils to be investigated and the test procedure were to remain the same as in the investigation with the pure TCE permeant.

As will be evident from the results of the investigation presented later in this report, it was not necessary to use the contingency plan.

7. RESULTS AND DISCUSSION

The laboratory testing of the clay soil material occurred in two phases. In the first phase, the applied pressures on the soil sample in the permeameter were in accordance with the test conditions specified in the Test Plan. The results of this phase of the investigation indicated that the permeability of the three types of clay soils were not only very low with TCE as the permeant, but were also lower (by approximately an order of magnitude) than that with water as the permeant.

This response of the clay soil material to TCE was not anticipated based on literature reports of similar clay liner studies with other organic solvents. It was, therefore, considered necessary to include a second phase of the investigation to evaluate the effect of a lower applied lateral pressure condition on the permeability of the clay soil. The rationale for selecting the lower lateral pressure test condition is discussed later in this section. The results of the laboratory investigations are discussed separately for the two phases of the work. For purposes of this report, Phase 1 and Phase 2 investigations are referred to as "high-pressure" and "low-pressure" conditions, respectively.

7.1 Phase 1 investigation. The permeability test results of the "high-pressure" condition for the three clay soils investigated are presented in Tables 7 through 9. The data show that for all three soil types, there is a high degree of reproducibility in the permeability results of the triplicate columns. All permeability results were derived using the model presented in Section 6.2.5 of this report.

The mean intrinsic permeability of the different clay soils (Kw, computed from daily mean permeabilities of the triplicate columns) for water (0.01N $CaSO_4$) were as follows:

(1) Local clay, $K_w = 4.19 \times 10^{-9}$ cm/ sec.
(2) Soil and Volclay mix, $K_w = 4.3 \times 10^{-9}$ cm/sec.
(3) Kaolinite, $K_w = 4.42 \times 10^{-8}$ cm/sec.

It can be seen that the local clay and the soil-Volclay mix have comparable permeabilities and that of kaolinite is higher by approximately one order of magnitude.

TABLE 7

PERMEABILITY TEST RESULTS

SOIL TYPE: LOCAL CLAY

PRESSURE: HIGH

	PERMEAMETER #1			PERMEAMETER #2			PERMEAMETER #3				
DAY	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	4.67	0.06	3.98E-09	4.95	0.07	3.90E-09	19.95	0.27	1.25E-08	0.08	6.78E-09
2	7.50	0.10	3.15E-09	7.52	0.10	2.52E-09	27.53	0.38	1.77E-08	0.17	7.79E-09
3	10.17	0.14	3.30E-09	9.80	0.13	3.41E-09	32.65	0.45	5.03E-09	0.23	3.91E-09
4	12.63	0.17	3.21E-09	11.72	0.16	2.44E-09	35.62	0.49	3.85E-09	0.27	3.17E-09
5	15.60	0.21	3.40E-09	14.07	0.19	2.38E-09	56.23	0.77	2.02E-08	0.36	8.65E-09
6	18.18	0.25	3.58E-09	15.92	0.22	2.60E-09	63.96	0.88	7.17E-09	0.44	4.45E-09
7	19.98	0.27	3.47E-09	17.24	0.24	2.51E-09	67.00	0.92	5.80E-09	0.46	3.93E-09
8	23.30	0.32	3.05E-09	19.73	0.27	2.27E-09	71.01	0.98	3.68E-09	0.49	3.00E-09
9	25.81	0.35	3.45E-09	21.39	0.29	2.40E-09	73.25	1.01	3.11E-09	0.55	2.99E-09
10	28.73	0.40	4.41E-09	23.26	0.32	2.47E-09	75.71	1.04	3.30E-09	0.58	3.39E-09
11	31.29	0.43	3.46E-09	25.15	0.35	2.30E-09	78.31	1.08	3.31E-09	0.61	3.02E-09
12	34.25	0.47	4.69E-09	27.12	0.37	3.02E-09	81.69	1.12	6.42E-09	0.65	4.71E-09
13	36.12	0.50	3.86E-09	28.51	0.39	2.84E-09	84.21	1.16	5.19E-09	0.66	3.96E-09
14	39.18	0.54	3.65E-09	30.79	0.42	2.71E-09	87.89	1.21	6.47E-09	0.70	4.28E-09
15	42.69	0.59	3.36E-09	33.55	0.46	2.60E-09	91.86	1.26	3.83E-09	0.74	3.26E-09
16	45.01	0.62	3.45E-09	35.39	0.49	2.49E-09	94.41	1.30	3.77E-09	0.79	3.23E-09
17	47.36	0.65	3.10E-09	37.26	0.51	2.27E-09	98.19	1.35	4.27E-09	0.83	3.21E-09
18	50.26	0.69	3.78E-09	39.61	0.54	3.06E-09	101.70	1.40	4.30E-09	0.87	3.71E-09
19	52.66	0.72	6.82E-09	41.37	0.57	2.20E-09	104.47	1.44	3.57E-09	0.90	4.20E-09
20	54.78	0.75	2.79E-09	42.94	0.59	1.97E-09	107.04	1.47	3.48E-09	0.93	2.75E-09
21	56.83	0.78	2.74E-09	44.67	0.61	2.30E-09	112.65	1.55	7.56E-09	0.95	4.20E-09
22	59.82	0.82	3.53E-09	47.02	0.65	2.75E-09	115.98	1.60	4.00E-09	1.00	3.43E-09
23	61.20	0.84	2.57E-09	48.05	0.66	1.91E-09	120.40	1.66	8.49E-09	1.03	4.32E-09
24	61.43	0.84	2.75E-10	48.32	0.66	3.14E-10	120.86	1.66	5.69E-10	1.05	3.86E-10
B. TCE											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	4.01	0.06	5.53E-09	2.92	0.04	4.23E-09	3.56	0.05	4.96E-09	0.03	4.91E-09
2	6.43	0.09	1.44E-09	4.49	0.06	6.43E-10	5.47	0.08	8.66E-10	0.07	9.84E-10
3	8.62	0.12	2.76E-09	6.13	0.08	2.21E-09	7.43	0.10	2.35E-09	0.10	2.44E-09
4	10.58	0.15	1.17E-09	7.75	0.11	2.22E-09	9.37	0.13	9.77E-09	0.12	4.39E-09
5	12.72	0.17	2.15E-08	9.19	0.13	2.14E-08	10.88	0.15	3.22E-08	0.15	2.50E-08
6	15.69	0.22	3.14E-09	11.29	0.16	2.20E-09	13.14	0.18	2.38E-09	0.16	2.57E-09
7	18.17	0.25	3.83E-09	14.78	0.20	4.06E-09	15.17	0.21	4.59E-09	0.21	4.16E-09
8	20.05	0.28	6.27E-10	16.83	0.23	2.29E-09	16.31	0.22	4.82E-10	0.24	1.13E-09
9	20.29	0.28	4.53E-10	18.02	0.25	2.33E-09	16.53	0.23	4.13E-10	0.24	1.07E-09
10	20.57	0.28	4.47E-10	19.43	0.27	6.75E-10	16.87	0.23	5.89E-10	0.26	5.70E-10
11	20.70	0.28	2.34E-10	20.25	0.28	1.55E-09	16.97	0.23	1.98E-10	0.26	6.60E-10
12	20.82	0.29	1.65E-10	20.39	0.28	1.91E-10	17.12	0.24	1.87E-10	0.27	1.81E-10
13	20.96	0.29	1.85E-10	20.41	0.28	2.34E-11	17.28	0.24	2.06E-10	0.27	1.38E-10
14	21.12	0.29	2.11E-10	20.52	0.28	1.42E-10	17.42	0.24	1.85E-10	0.27	1.79E-10
15	21.27	0.29	1.86E-10	20.62	0.28	1.41E-10	17.54	0.24	1.61E-10	0.27	1.63E-10
16	21.39	0.29	1.64E-10	20.82	0.29	2.60E-10	17.65	0.24	1.39E-10	0.27	1.87E-10
17	21.51	0.30	1.61E-10	20.98	0.29	2.09E-10	17.81	0.24	2.04E-10	0.28	1.91E-10

TABLE 8

PERMEABILITY TEST RESULTS
SOIL TYPE: SOIL & VOLCLAY
PRESSURE: HIGH

DAY	PERMEAMETER #4 TOTAL VOLUME (ML)	PERMEAMETER #4 PORE VOLUME	PERMEAMETER #4 PERM (CM/SEC)	PERMEAMETER #5 TOTAL VOLUME (ML)	PERMEAMETER #5 PORE VOLUME	PERMEAMETER #5 PERM (CM/SEC)	PERMEAMETER #6 TOTAL VOLUME (ML)	PERMEAMETER #6 PORE VOLUME	PERMEAMETER #6 PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	2.67	0.06	2.18E-09	3.29	0.07	2.69E-09	3.12	0.07	2.54E-09	0.06	2.47E-09
2	4.81	0.10	3.39E-09	6.06	0.13	4.40E-09	5.79	0.12	4.25E-09	0.12	4.01E-09
3	9.44	0.20	6.01E-09	9.26	0.20	5.27E-09	20.13	0.43	4.58E-09	0.28	5.29E-09
4	14.78	0.32	6.83E-09	14.02	0.30	4.55E-09	24.81	0.53	5.66E-09	0.38	5.68E-09
5	19.27	0.41	4.97E-09	17.28	0.37	3.37E-09	28.05	0.60	3.45E-09	0.46	3.93E-09
6	22.03	0.47	2.08E-09	19.45	0.42	2.26E-09	30.28	0.65	2.38E-09	0.51	2.24E-09
7	27.18	0.58	8.79E-09	22.74	0.49	5.50E-09	33.61	0.72	5.88E-09	0.60	6.72E-09
8	32.82	0.70	7.61E-09	26.43	0.57	4.90E-09	37.51	0.80	5.21E-09	0.69	5.91E-09
9	36.87	0.79	4.48E-09	30.12	0.65	4.26E-09	41.12	0.88	4.15E-09	0.77	4.29E-09
10	40.70	0.87	5.22E-09	33.46	0.72	4.36E-09	44.44	0.95	4.43E-09	0.85	4.67E-09
11	44.61	0.96	5.04E-09	36.58	0.79	3.99E-09	47.50	1.02	3.88E-09	0.92	4.30E-09
12	48.73	1.05	5.56E-09	40.00	0.86	4.29E-09	50.81	1.09	4.19E-09	1.00	4.68E-09
13	52.01	1.12	4.34E-09	42.67	0.92	3.57E-09	53.47	1.15	3.43E-09	1.06	3.78E-09
14	54.41	1.17	4.51E-09	44.51	0.96	3.41E-09	55.30	1.19	3.42E-09	1.10	3.78E-09
15	58.67	1.26	4.00E-09	48.16	1.03	3.39E-09	59.00	1.27	3.46E-09	1.19	3.62E-09
16	62.44	1.34	3.37E-09	51.13	1.10	2.91E-09	61.93	1.33	2.78E-09	1.26	3.02E-09
17	65.77	1.41	6.90E-09	54.27	1.16	5.13E-09	64.95	1.39	4.79E-09	1.32	5.61E-09
18	69.16	1.48	4.60E-09	56.87	1.22	3.26E-09	67.45	1.45	2.78E-09	1.38	3.54E-09
B. TCE											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	4.26	0.09	9.17E-09	3.92	0.08	5.68E-09	3.40	0.07	3.76E-09	0.08	6.21E-09
2	8.67	0.19	7.96E-09	6.32	0.14	3.66E-09	6.30	0.14	3.39E-09	0.15	5.00E-09
3	10.94	0.23	3.93E-09	8.67	0.19	4.07E-09	8.50	0.18	3.79E-09	0.20	3.93E-09
4	15.16	0.33	4.02E-09	12.09	0.26	3.24E-09	11.54	0.25	2.88E-09	0.28	3.38E-09
5	15.69	0.34	9.75E-10	12.89	0.28	6.22E-10	13.68	0.29	3.74E-09	0.30	1.78E-09
6	15.90	0.34	3.42E-10	13.09	0.28	6.78E-10	14.85	0.32	6.84E-10	0.31	5.68E-10
7	17.93	0.38	5.51E-10	16.37	0.35	3.58E-09	17.35	0.37	1.85E-09	0.37	1.99E-09
8	18.40	0.39	6.86E-10	17.04	0.37	6.10E-10	17.86	0.38	5.31E-10	0.38	6.09E-10
9	19.23	0.41	2.39E-09	17.31	0.37	3.52E-10	18.09	0.39	2.10E-10	0.39	9.86E-10
10	19.98	0.43	8.84E-10	17.49	0.38	2.45E-10	18.27	0.39	2.43E-10	0.40	4.57E-10
12	20.11	0.43	2.61E-10	17.85	0.38	2.61E-10	18.59	0.40	1.94E-10	0.40	2.39E-10
13	20.25	0.43	5.42E-11	18.02	0.39	2.17E-10	18.79	0.40	2.16E-10	0.41	1.62E-10
14	20.52	0.44	2.90E-10	18.18	0.39	2.90E-10	18.93	0.41	2.88E-10	0.41	2.90E-10
15	21.16	0.45	1.37E-09	18.31	0.39	2.67E-10	19.04	0.41	2.27E-10	0.42	6.22E-10
16	21.30	0.46	2.67E-10	18.47	0.40	2.67E-10	19.18	0.41	8.83E-11	0.42	2.07E-10
17	21.44	0.46	2.25E-10	18.58	0.40	1.68E-10	19.31	0.41	1.95E-10	0.42	1.96E-10
18	21.64	0.46	1.46E-09	18.74	0.40	8.12E-10	19.45	0.42	4.84E-10	0.43	9.20E-10
19	21.80	0.47	2.43E-10	18.97	0.41	2.43E-10	19.61	0.42	1.61E-10	0.43	2.16E-10
20	21.96	0.47	2.10E-10	19.09	0.41	2.79E-10	19.73	0.42	1.39E-10	0.43	2.09E-10
21	22.10	0.47	2.10E-10	19.22	0.41	2.80E-10	19.89	0.43	2.78E-10	0.44	2.56E-10
22	22.26	0.48	2.99E-10	19.38	0.42	2.24E-10	20.04	0.43	2.22E-10	0.44	2.48E-10
23	22.37	0.48	2.01E-10	19.50	0.42	2.34E-10	20.11	0.43	1.33E-10	0.44	1.89E-10
24	22.57	0.48	2.79E-10	19.61	0.42	2.09E-10	20.29	0.44	2.42E-10	0.45	2.43E-10
25	22.65	0.49	1.16E-10	19.73	0.42	1.62E-10	20.39	0.44	1.38E-10	0.45	1.39E-10
26	22.76	0.49	1.41E-10	19.86	0.43	1.64E-10	20.52	0.44	1.63E-10	0.45	1.56E-10
27	22.92	0.49	2.10E-10	20.00	0.43	1.86E-10	20.64	0.44	1.62E-10	0.45	1.86E-10
28	23.03	0.49	1.41E-10	20.13	0.43	1.64E-10	20.75	0.45	1.39E-10	0.46	1.48E-10
29	23.19	0.50	2.07E-10	20.29	0.44	2.07E-10	20.91	0.45	2.06E-10	0.46	2.07E-10
30	23.31	0.50	1.66E-10	20.39	0.44	1.42E-10	21.02	0.45	1.41E-10	0.46	1.50E-10

TABLE 9

PERMEABILITY TEST RESULTS

SOIL TYPE: KAOLINITE

PRESSURE: HIGH

	PERMEAMETER #7			PERMEAMETER #8			PERMEAMETER #9				
DAY	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	31.93	0.32	4.32E-08	44.22	0.45	9.45E-08	31.35	0.32	4.00E-08	0.36	5.92E-08
2	53.55	0.54	4.70E-08	67.05	0.68	4.95E-08	53.98	0.55	4.91E-08	0.59	4.85E-08
3	65.04	0.66	2.95E-08	69.17	0.70	5.27E-09	63.37	0.64	2.40E-08	0.67	1.96E-08
4	82.14	0.83	3.48E-08	75.53	0.76	1.24E-08	77.87	0.79	2.90E-08	0.79	2.54E-08
5	97.97	0.99	4.02E-08	82.58	0.84	9.35E-09	91.38	0.92	3.44E-08	0.92	2.80E-08
6	120.25	1.22	9.24E-08	94.95	0.96	1.17E-07	110.15	1.11	5.21E-08	1.10	8.73E-08
7	142.84	1.44	9.26E-08	118.33	1.20	9.44E-08	132.72	1.34	1.03E-07	1.33	9.65E-08
8	156.89	1.59	4.55E-08	128.27	1.30	2.65E-08	143.35	1.45	3.44E-08	1.44	3.55E-08
9	171.17	1.73	4.90E-09	131.65	1.33	7.52E-09	161.39	1.63	1.17E-08	1.56	8.03E-09
10	172.35	1.74	2.30E-09	134.20	1.36	4.90E-09	167.97	1.70	1.31E-08	1.60	6.76E-09
11	188.39	1.90	2.44E-06	151.83	1.54	2.53E-06	186.70	1.89	4.69E-06	1.78	3.22E-06
12	210.66	2.13	6.31E-08	173.74	1.76	6.22E-08	209.07	2.11	6.34E-08	2.00	6.29E-08
13	234.77	2.37	1.42E-09	176.92	1.79	2.13E-10	231.78	2.34	1.27E-09	2.17	9.68E-10
14	260.72	2.64	5.68E-08	179.19	1.81	7.62E-09	255.16	2.58	4.94E-08	2.34	3.79E-08
15	292.62	2.96	4.86E-08	201.66	2.04	7.38E-09	299.49	3.03	4.18E-08	2.68	3.26E-08
16	306.06	3.09	3.84E-08	203.43	2.06	4.80E-09	311.43	3.15	3.37E-08	2.77	2.56E-08
17	330.79	3.34	4.89E-08	205.22	2.08	1.06E-09	335.61	3.39	3.07E-08	2.94	2.69E-08
18	357.57	3.62	5.04E-08	226.47	2.29	9.77E-10	361.44	3.65	4.75E-08	3.19	3.30E-08
B. TCE											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	3.19	0.03	2.85E-08	2.26	0.02	2.13E-08	3.23	0.03	2.93E-08	0.03	2.64E-08
2	23.38	0.24	2.06E-09	2.85	0.03	2.18E-09	20.86	0.21	2.07E-09	0.16	2.10E-09
3	23.92	0.24	6.80E-10	3.26	0.03	1.54E-09	21.30	0.22	5.83E-10	0.16	9.35E-10
4	24.29	0.25	1.25E-09	3.56	0.04	1.10E-09	21.55	0.22	5.19E-10	0.17	9.55E-10
5	24.63	0.25	5.15E-10	3.76	0.04	7.62E-10	21.80	0.22	4.12E-10	0.17	5.63E-10
6	24.77	0.25	3.89E-10	3.85	0.04	2.57E-10	21.93	0.22	3.40E-10	0.17	3.28E-10
7	24.93	0.25	2.91E-10	3.99	0.04	2.74E-10	22.09	0.22	2.91E-10	0.17	2.85E-10
8	25.08	0.25	2.62E-10	4.15	0.04	3.11E-10	22.23	0.22	2.62E-10	0.17	2.78E-10
9	25.24	0.26	2.93E-10	4.26	0.04	2.06E-10	22.39	0.23	2.93E-10	0.17	2.64E-10
10	25.38	0.26	2.62E-10	4.36	0.04	2.07E-10	22.53	0.23	2.61E-10	0.18	2.43E-10

Since the permeabilities of the clay soil materials generally were low, it was necessary to run the tests with water for about 18 to 24 days in order to permeate a minimum of one pore volume of water through the soil samples, although permeability equilibrium was reached earlier. The total mean pore volume permeated ranged from 1.05 for the local clay to 3.19 for the kaolinite.

The effect of TCE on the permeability of the different clay soil is tabulated in Tables 7 through 9 and shown graphically in Figures 7 through 10. These figures show the permeability trend with time/pore volume for both water and TCE as permeant. The trend line is shown to indicate the significant decrease in permeability between water and TCE. In all three soil types, a slight increase in permeability was observed during the first four to seven days after the permeant was changed from water to TCE. This change could have been due to some of the mechanical alterations in the operation of the equipment when changing the permeant. However, the increase was not significant since the permeability remained within the same order of magnitude as that with water. As seen in these figures, the permea- bility decreased significantly (approximately by one order of magnitude) and reached an equilibrium in all three clay soils. The mean permeability at equilibrium, for the three soil types when subjected to K_{TCE}, was computed as follows:

(1) Local clay, $K_{TCE} = 2.84 \times 10^{-10}$ cm/ sec.
(2) Soil and Volclay mix, $K_{TCE} = 3.25 \times 10^{-10}$ cm/sec.
(3) Kaolinite, $K_{TCE} = 4.81 \times 10^{-10}$ cm/sec.

Based on these results, it appears that the permeability of the soils was approximately one order of magnitude lower with TCE than that with water. However, the mean pore volume permeated with TCE was much lower than that with water and ranged from 0.18 for the kaolinite to 0.46 for the soil-Volclay mix. Permeability-equilibrium was reached at the lower permeability with TCE.

The results of the Phase 1 investigations showed a significant difference in permeability effects of TCE on the clay soils in comparison to that generally reported in literature for other organic solvents. Studies by other investigators using rigid and flexible wall permeameters and organic solvents show that the permeability of clay soils increased significantly when the permeant is changed from water to an organic solvent. (7, 14, 15, 16, 17) The results of this investigation indicated a decrease in permeability when the clay soils were impacted with the organic solvent TCE. One of the considerations hypothesized was that the lateral pressure acting on the clay liner sample may be sealing the cracks that might be formed due to the effect of the TCE on the clay structure. Consequently, the actual permeability of the clay soil may be higher than that observed.

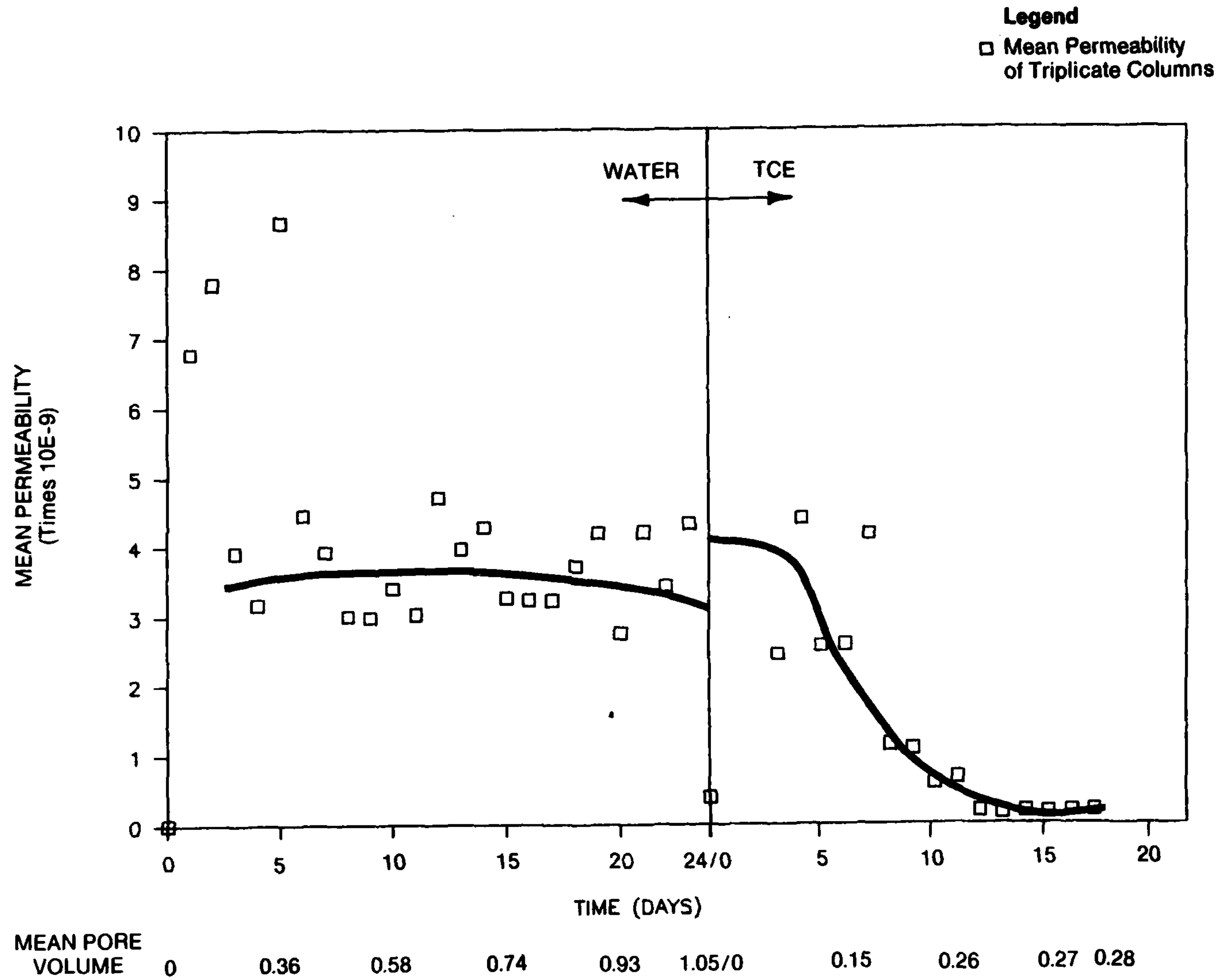


FIGURE 7 LOCAL CLAY: PERMEABILITY TRENDS AT HIGH LATERAL PRESSURE

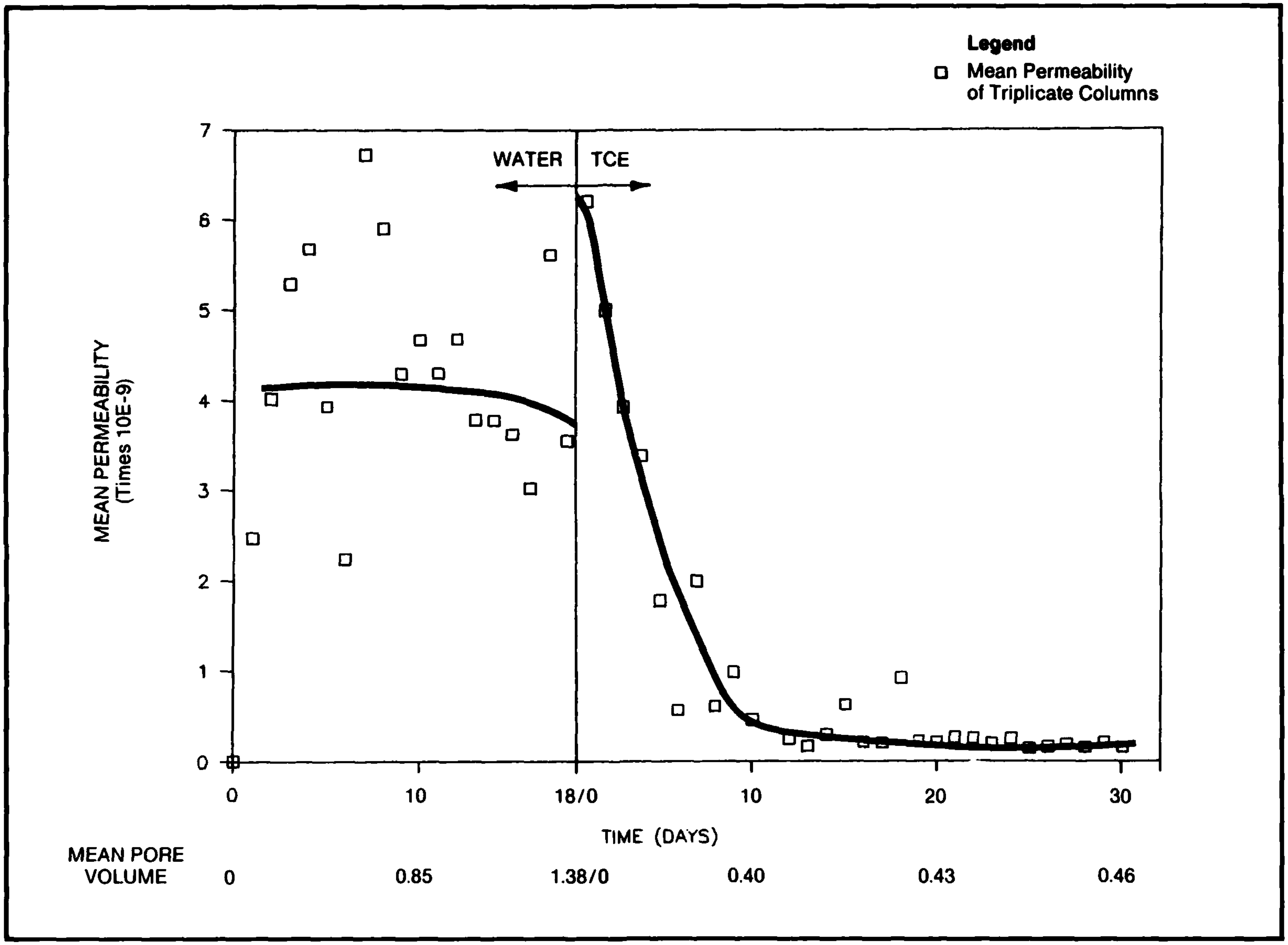


FIGURE 8 SOIL & VOLCLAY: PERMEABILITY TRENDS AT HIGH LATERAL PRESSURE

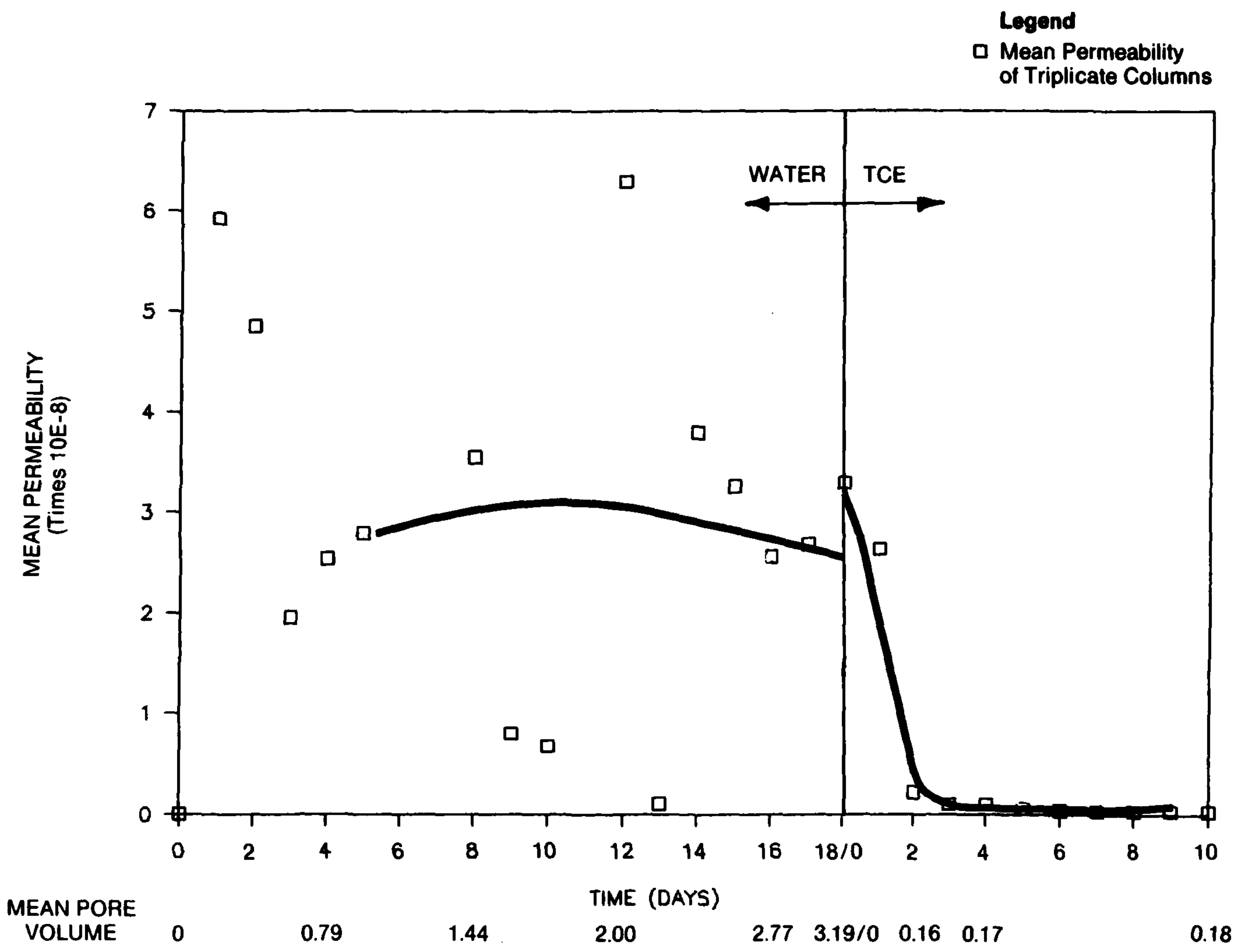


FIGURE 9 KAOLINITE: PERMEABILITY TRENDS AT HIGH LATERAL PRESSURE

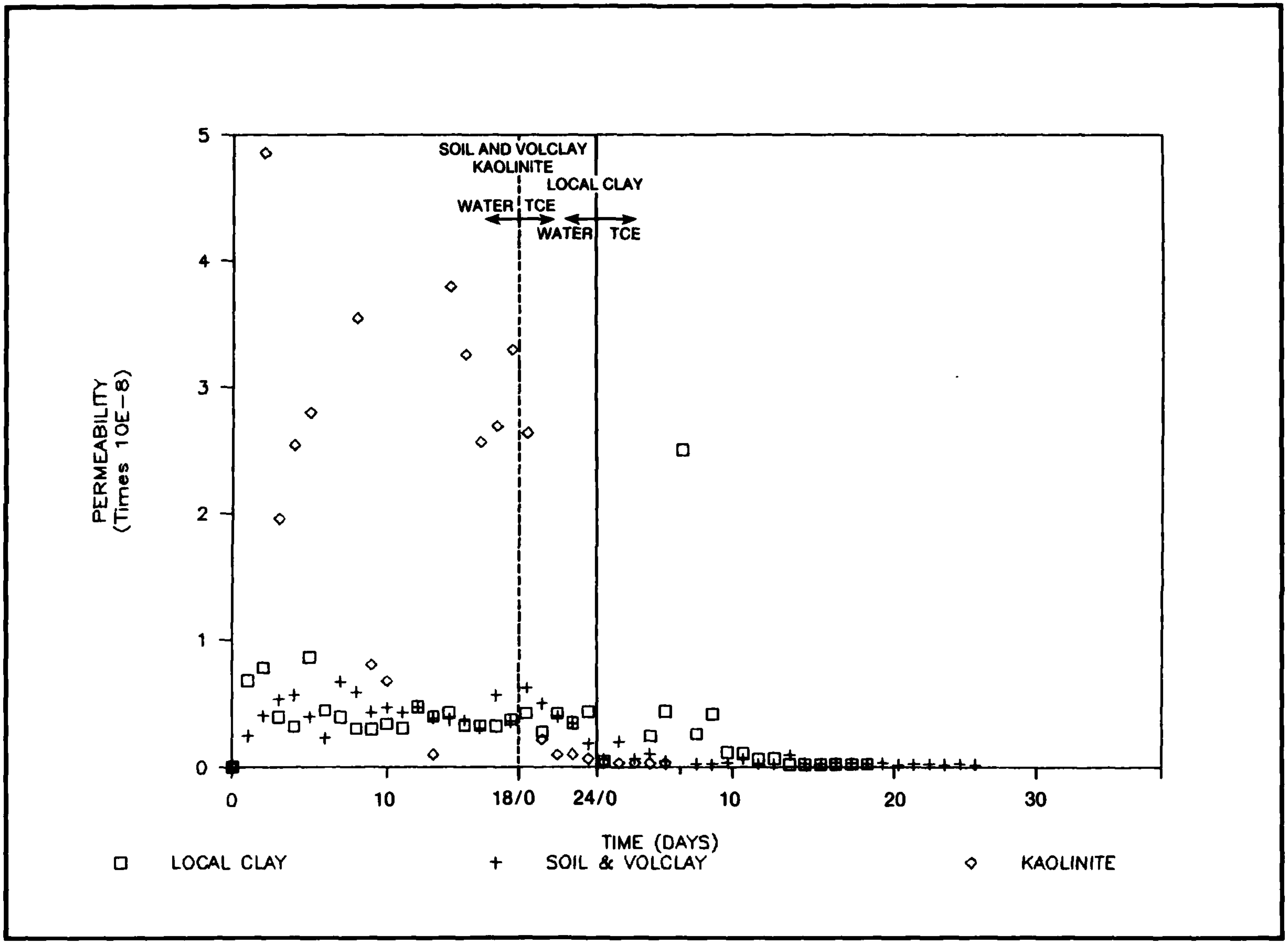


FIGURE 10 PERMEABILITY TRENDS OF DIFFERENT CLAYS
AT HIGH LATERAL PRESSURE

In order to determine whether the lateral pressure was influencing the permeability, it was decided to conduct the Phase 2 investigation utilizing a lower lateral pressure in the permeameter. The lateral pressure was decreased by 15 psig in the Phase 2 investigation. The basis of this selection of lateral pressure was that it represents a considerable decrease in overburden pressure at field conditions. It is equivalent to removal of pressure caused by 20 feet of saturated overburden soil at a density of 110 lb/cu ft.

7.2 Phase 2 investigation. The Phase 2 investigation tested the same three types of clay soils as in Phase 1 but under lower lateral pressure conditions. The permeability test results for the three clay soils are presented in Tables 10 through 12. The test results show a good consistency in values between the triplicate columns.

Based on the data, the mean intrinsic permeability of the three clays for the water permeant are computed as follows:

(1) Local clay, $K_w = 5.36 \times 10^{-9}$ cm/sec.
(2) Soil and Volclay, $K_w = 3.12 \times 10^{-9}$ cm/sec.
(3) Kaolinite, $K_w = 4.38 \times 10^{-8}$ cm/sec.

The number of pore volumes of water permeated ranged from 0.74 for soil-Volclay mix to 3.72 for kaolinite. The intrinsic permeability of the three clays for water are comparable to that found in the Phase 1 investigation.

The effect of TCE on the permeability of the clays under lower lateral pressure conditions are presented in Tables 7 through 9 and shown graphically in Figures 9 through 12. From the data, the mean permeability of the three clays are computed as follows:

(1) Local clay, $K_{TCE} = 4.12 \times 10^{-10}$ cm/sec.
(2) Soil and Volclay, $K_{TCE} = 4.92 \times 10^{-10}$ cm/sec.
(3) Kaolinite, $K_{TCE} = 3.92 \times 10^{-10}$ cm/sec.

With TCE, the number of pore volumes permeated was much less than water and ranged from 0.34 for soil-Volclay mix to 0.51 for local clay.

Figures 11 through 14 show that the permeability of the clays with TCE as the permeant is lower than that with water. These results are comparable to the Phase 1 findings. In this case also the difference in permeability is approximately one order of magnitude.

TABLE 10

PERMEABILITY TEST RESULTS

SOIL TYPE: LOCAL CLAY

PRESSURE: LOW

DAY	PERMEAMETER #1 TOTAL VOLUME (ML)	PERMEAMETER #1 PORE VOLUME	PERMEAMETER #1 PERM (CM/SEC)	PERMEAMETER #2 TOTAL VOLUME (ML)	PERMEAMETER #2 PORE VOLUME	PERMEAMETER #2 PERM (CM/SEC)	PERMEAMETER #3 TOTAL VOLUME (ML)	PERMEAMETER #3 PORE VOLUME	PERMEAMETER #3 PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	7.93	0.17	8.18E-09	3.92	0.08	3.95E-09	4.92	0.11	5.00E-09	0.12	5.71E-09
2	15.16	0.33	1.84E-08	7.60	0.16	6.76E-09	9.65	0.21	8.83E-09	0.23	1.13E-08
4	23.71	0.51	2.08E-08	11.36	0.24	6.20E-09	14.28	0.31	7.83E-09	0.35	1.16E-08
5	29.72	0.64	1.08E-08	13.91	0.30	4.48E-09	17.99	0.39	6.54E-09	0.44	7.27E-09
6	37.40	0.80	1.41E-08	17.56	0.38	6.41E-09	22.83	0.49	8.61E-09	0.56	9.71E-09
7	44.04	0.95	6.13E-08	26.50	0.57	1.21E-07	26.93	0.58	3.90E-08	0.70	7.38E-08
11	58.02	1.25	7.08E-09	37.94	0.81	5.70E-09	35.51	0.76	4.25E-09	0.94	5.67E-09
13	70.37	1.51	7.71E-09	45.59	0.98	4.19E-09	42.90	0.92	4.33E-09	1.14	5.41E-09
14	74.87	1.61	8.36E-09	47.86	1.03	4.14E-09	45.68	0.98	5.10E-09	1.20	5.87E-09
16	83.76	1.80	8.39E-09	52.49	1.13	4.21E-09	51.36	1.10	5.21E-09	1.34	5.93E-09
18	94.46	2.03	9.42E-09	57.33	1.23	4.15E-09	57.88	1.24	5.63E-09	1.50	6.40E-09
19	96.82	2.08	4.79E-09	58.63	1.26	2.52E-09	59.57	1.28	3.33E-09	1.54	3.54E-09
24	113.72	2.44	6.49E-09	68.37	1.47	3.62E-09	70.06	1.50	3.93E-09	1.80	4.68E-09
B. TCE											
0	0.87	0.02	0.00E+00	0.41	0.01	0.00E+00	0.11	0.00	0.00E+00	0.01	0.00E+00
1	7.25	0.16	1.31E-08	7.21	0.15	1.39E-08	3.83	0.08	7.59E-09	0.13	1.16E-08
3	14.02	0.30	6.41E-09	10.42	0.22	2.98E-09	10.37	0.22	6.06E-09	0.25	5.15E-09
6	32.54	0.70	1.64E-08	15.65	0.34	4.44E-09	12.41	0.27	1.71E-09	0.43	7.53E-09
12	33.07	0.71	5.21E-10	16.69	0.36	6.82E-10	13.50	0.29	6.32E-10	0.45	6.11E-10
14	33.43	0.72	6.37E-10	17.08	0.37	7.25E-10	13.89	0.30	7.09E-10	0.46	6.90E-10
15	33.57	0.72	8.47E-11	17.22	0.37	8.77E-11	14.02	0.30	7.49E-11	0.46	8.24E-11
18	33.95	0.73	6.73E-10	19.80	0.42	4.85E-09	14.37	0.31	6.49E-10	0.49	2.06E-09
20	34.14	0.73	1.37E-10	19.93	0.43	1.99E-10	14.64	0.31	1.66E-10	0.49	1.67E-10
21	34.32	0.74	3.99E-10	20.07	0.43	3.30E-10	14.80	0.32	3.63E-10	0.49	3.64E-10
22	34.39	0.74	4.19E-11	20.18	0.43	6.51E-11	14.87	0.32	4.24E-11	0.50	4.98E-11
25	34.75	0.75	4.06E-10	20.52	0.44	3.99E-10	15.39	0.33	5.96E-10	0.51	4.67E-10
28	35.05	0.75	1.91E-10	20.78	0.45	1.65E-10	15.48	0.33	1.61E-10	0.51	1.72E-10

TABLE 11

PERMEABILITY TEST RESULTS

SOIL TYPE: SOIL & VOLCLAY

PRESSURE: LOW

	PERMEAMETER #4			PERMEAMETER #5			PERMEAMETER #6				
DAY	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
2	2.94	0.06	3.26E-09	3.94	0.08	3.96E-09	2.08	0.04	8.14E-09	0.06	5.12E-09
3	4.36	0.09	2.65E-09	5.77	0.12	3.46E-09	2.65	0.06	1.07E-09	0.09	2.39E-09
4	5.91	0.13	8.18E-09	7.75	0.17	3.39E-09	4.27	0.09	2.56E-09	0.13	4.71E-09
5	6.95	0.15	2.52E-09	9.03	0.19	3.19E-09	5.29	0.11	2.49E-09	0.15	2.73E-09
6	8.32	0.18	2.01E-09	10.83	0.23	2.70E-09	6.87	0.15	2.33E-09	0.19	2.35E-09
7	10.01	0.21	1.12E-08	13.02	0.28	1.93E-08	8.71	0.19	1.56E-08	0.23	1.54E-08
10	11.99	0.26	1.32E-09	15.48	0.33	1.62E-09	11.17	0.24	1.63E-09	0.28	1.52E-09
12	15.33	0.33	3.22E-09	19.72	0.42	4.03E-09	15.12	0.32	3.63E-09	0.36	3.63E-09
13	16.99	0.36	3.17E-09	21.73	0.47	3.84E-09	16.94	0.36	3.48E-09	0.40	3.50E-09
15	19.72	0.42	2.58E-09	24.95	0.54	3.05E-09	20.02	0.43	2.92E-09	0.46	2.85E-09
18	24.68	0.53	4.04E-09	30.47	0.65	3.91E-09	25.59	0.55	4.31E-09	0.58	4.09E-09
23	31.03	0.67	2.38E-09	38.52	0.83	3.02E-09	31.13	0.67	2.08E-09	0.72	2.49E-09
24	31.93	0.69	2.26E-09	39.57	0.85	2.63E-09	31.70	0.68	1.41E-09	0.74	2.10E-09
B. TCE											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	1.66	0.04	3.35E-09	1.96	0.04	3.95E-09	1.49	0.03	3.02E-09	0.04	3.44E-09
8	10.29	0.22	2.11E-09	5.06	0.11	2.51E-09	10.54	0.23	1.86E-09	0.19	2.16E-09
12	13.36	0.29	1.39E-09	8.69	0.19	1.66E-09	11.17	0.24	2.78E-10	0.24	1.11E-09
15	14.82	0.32	9.81E-10	10.26	0.22	1.06E-09	11.56	0.25	2.56E-10	0.26	7.67E-10
16	15.28	0.33	8.61E-10	10.83	0.23	1.07E-09	11.70	0.25	2.57E-10	0.27	7.30E-10
19	16.21	0.35	5.74E-10	12.84	0.28	1.27E-09	12.59	0.27	5.34E-10	0.30	7.92E-10
20	16.47	0.35	4.89E-10	13.18	0.28	6.20E-10	13.61	0.29	1.85E-09	0.31	9.88E-10
21	16.62	0.36	2.09E-10	13.39	0.29	3.15E-10	14.64	0.31	1.52E-09	0.32	6.83E-10
22	16.79	0.36	2.78E-10	13.59	0.29	3.07E-10	14.87	0.32	3.64E-10	0.32	3.17E-10
23	16.90	0.36	2.29E-10	13.71	0.29	2.68E-10	14.96	0.32	1.93E-10	0.33	2.30E-10
26	17.29	0.37	2.38E-10	14.16	0.30	2.72E-10	15.39	0.33	2.62E-10	0.34	2.57E-10
28	17.49	0.38	2.27E-10	14.30	0.31	1.66E-10	15.57	0.33	2.08E-10	0.34	2.00E-10
29	17.61	0.38	1.76E-10	14.44	0.31	2.02E-10	15.69	0.34	1.78E-10	0.34	1.85E-10
30	17.76	0.38	2.59E-10	14.60	0.31	2.92E-10	15.83	0.34	2.61E-10	0.34	2.70E-10

TABLE 12

PERMEABILITY TEST RESULTS

SOIL TYPE: KAOLINITE

PRESSURE: LOW

	PERMEAMETER #7			PERMEAMETER #8			PERMEAMETER #9				
DAY	TOTAL VOLUME (ML)	PORE VOLUME	PERMEABILITY (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERMEABILITY (CM/SEC)	TOTAL VOLUME (ML)	PORE VOLUME	PERM (CM/SEC)	MEAN PORE VOLUME	MEAN PERMEABILITY (CM/SEC)
A. WATER											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
2	14.35	0.31	4.76E-08	15.01	0.32	4.97E-08	2.85	0.06	9.01E-09	0.23	3.54E-08
3	29.49	0.63	2.88E-08	30.51	0.65	2.95E-08	18.40	0.39	2.96E-08	0.56	2.93E-08
4	40.61	0.87	5.59E-08	44.49	0.95	5.84E-08	31.33	0.67	6.19E-08	0.83	5.87E-08
6	53.73	1.15	2.54E-08	55.64	1.19	2.84E-08	42.69	0.92	2.62E-08	1.09	2.67E-08
7	63.40	1.36	3.74E-08	62.07	1.33	2.41E-08	48.41	1.04	2.16E-08	1.24	2.77E-08
8	68.69	1.47	2.50E-08	71.12	1.53	4.16E-08	57.95	1.24	4.42E-08	1.41	3.69E-08
10	90.97	1.95	7.33E-08	94.95	2.04	6.03E-08	82.07	1.76	6.59E-08	1.92	6.65E-08
12	112.02	2.40	8.59E-08	116.76	2.51	8.52E-08	101.91	2.19	9.39E-08	2.37	8.83E-08
15	135.80	2.91	1.81E-09	141.13	3.03	2.14E-09	128.14	2.75	2.16E-09	2.90	2.04E-09
16	136.16	2.92	1.40E-09	142.18	3.05	4.13E-09	133.91	2.87	2.34E-08	2.95	9.64E-09
17	146.61	3.15	2.71E-08	153.06	3.28	4.43E-10	144.08	3.09	2.82E-08	3.17	1.86E-08
18	159.77	3.43	4.67E-08	166.52	3.57	4.78E-08	159.31	3.42	5.45E-08	3.47	4.96E-08
19	161.14	3.46	4.20E-09	168.06	3.61	4.69E-09	160.88	3.45	4.79E-09	3.51	4.56E-09
24	170.66	3.66	4.12E-08	177.94	3.82	4.25E-08	172.01	3.69	4.84E-08	3.72	4.41E-08
B. TCE											
0	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00	0.00E+00	0.00	0.00E+00
1	20.43	0.44	2.75E-08	12.75	0.27	4.93E-09	17.79	0.38	1.63E-08	0.36	1.62E-08
3	20.82	0.45	6.44E-10	13.14	0.28	6.04E-10	18.72	0.40	1.48E-09	0.38	9.08E-10
6	21.18	0.45	4.04E-10	13.59	0.29	4.75E-10	19.38	0.42	7.30E-10	0.39	5.36E-10
8	21.46	0.46	4.45E-10	13.91	0.30	4.70E-10	19.77	0.42	5.98E-10	0.39	5.04E-10
12	21.85	0.47	3.32E-10	14.34	0.31	3.40E-10	20.29	0.44	4.28E-10	0.40	3.67E-10
14	22.12	0.47	4.90E-10	14.62	0.31	4.91E-10	20.62	0.44	6.09E-10	0.41	5.30E-10
15	22.23	0.48	3.59E-10	14.75	0.32	3.94E-10	20.73	0.44	3.52E-10	0.41	3.69E-10
18	22.48	0.48	2.79E-10	15.03	0.32	3.00E-10	21.03	0.45	3.32E-10	0.42	3.04E-10
19	22.58	0.48	3.62E-10	15.14	0.32	3.41E-10	21.14	0.45	3.56E-10	0.42	3.53E-10
20	22.65	0.49	2.08E-10	15.23	0.33	2.44E-10	21.23	0.46	2.55E-10	0.42	2.36E-10
21	22.76	0.49	2.89E-10	15.33	0.33	2.71E-10	21.34	0.46	2.83E-10	0.43	2.81E-10
22	22.83	0.49	2.83E-10	15.42	0.33	3.33E-10	21.43	0.46	3.48E-10	0.43	3.21E-10
25	23.14	0.50	3.41E-10	15.74	0.34	3.40E-10	21.75	0.47	3.55E-10	0.43	3.45E-10
27	23.26	0.50	2.68E-10	15.90	0.34	3.24E-10	21.92	0.47	3.76E-10	0.44	3.23E-10
28	23.31	0.50	1.40E-10	15.96	0.34	1.32E-10	21.96	0.47	9.19E-11	0.44	1.21E-10
29	23.42	0.50	3.60E-10	16.08	0.35	3.95E-10	22.08	0.47	4.13E-10	0.44	3.89E-10

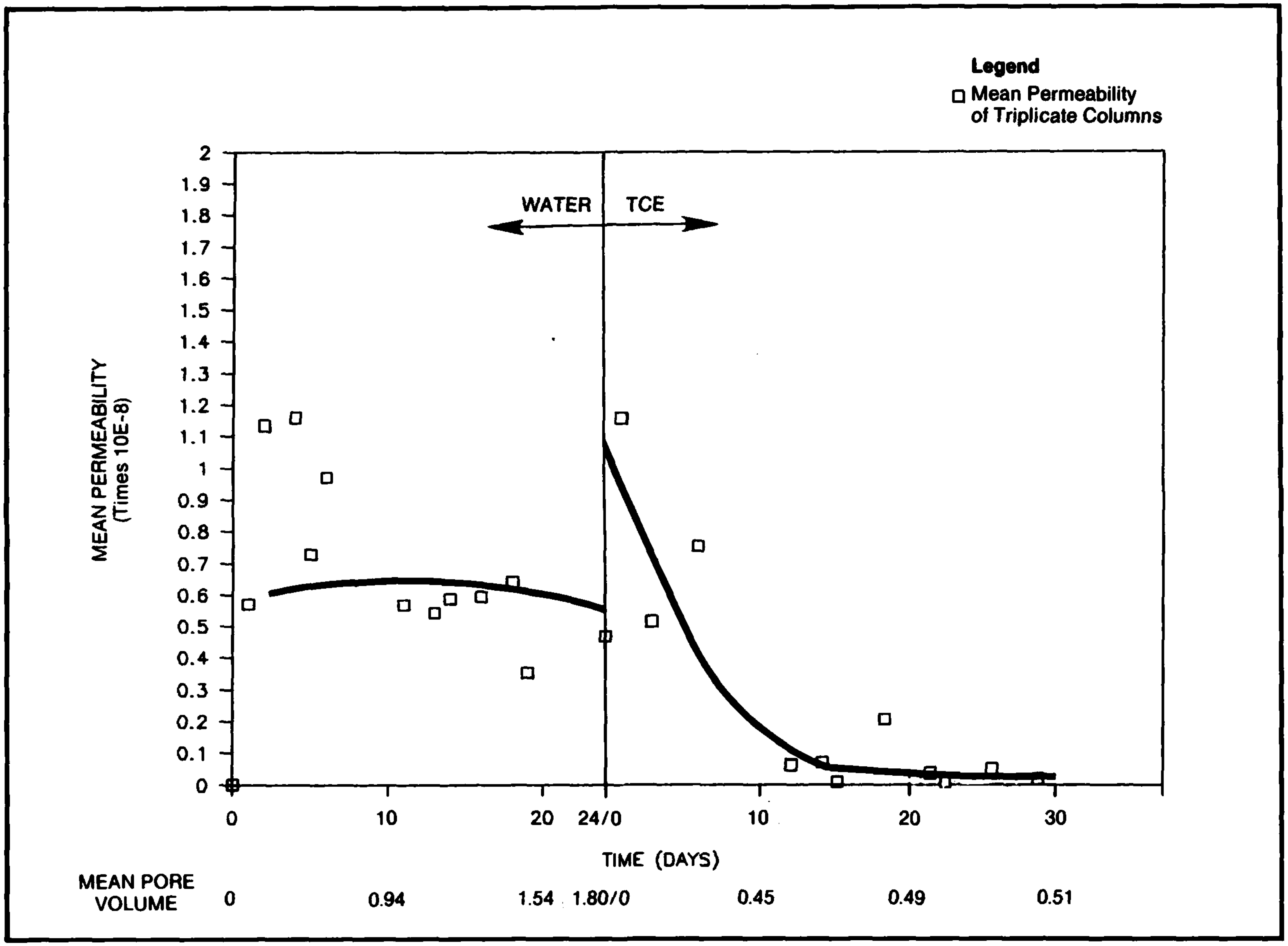


FIGURE 11 LOCAL CLAY: PERMEABILITY TRENDS AT LOW LATERAL PRESSURE

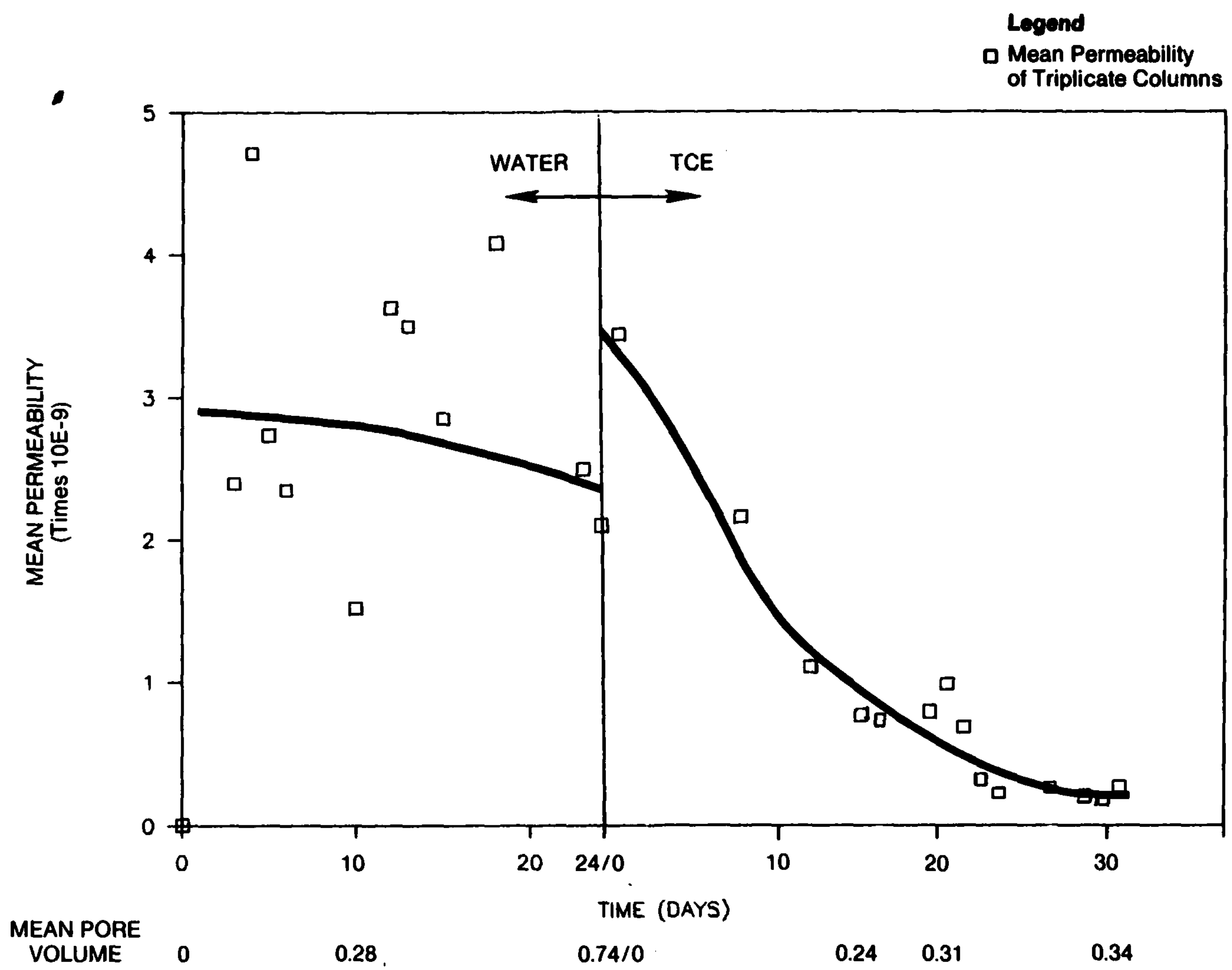


FIGURE 12 SOIL & VOLCLAY: PERMEABILITY TRENDS AT LOW LATERAL PRESSURE

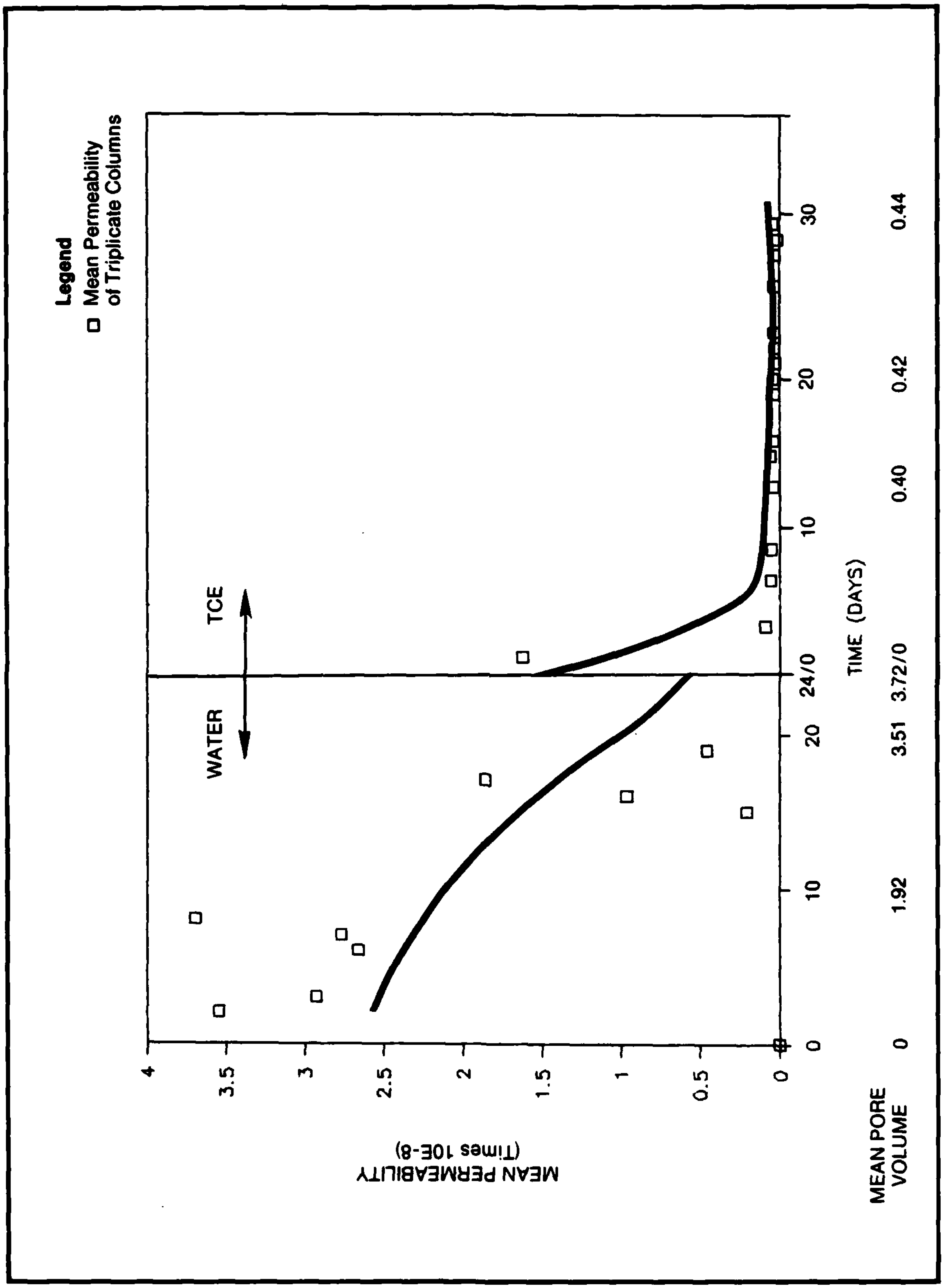


FIGURE 13 KAOLINITE: PERMEABILITY TRENDS AT LOW LATERAL PRESSURE

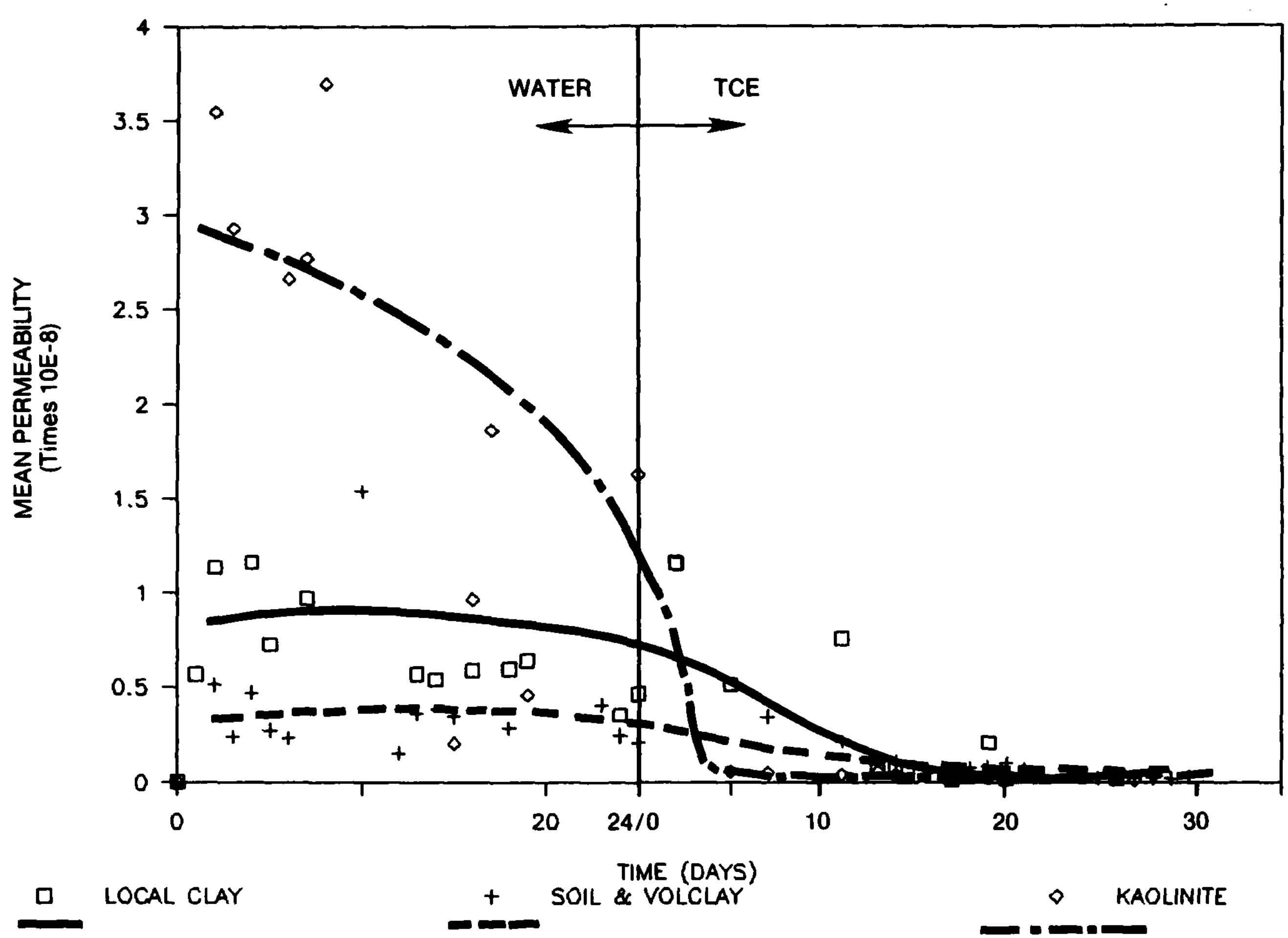


FIGURE 14 PERMEABILITY TRENDS OF DIFFERENT CLAYS AT LOW LATERAL PRESSURE

The comparison of permeability data between the high- and low-pressure test conditions for the three clay liners are presented in Tables 13 through 15 and graphically represented in Figures 15 through 17. These data and figures show that for both water and TCE there does not appear to be a significant difference in permeability for the three clays between the high-pressure and low-pressure test conditions. This finding, however, is based on limited data utilizing two test pressure conditions. In order to fully determine the effect of pressure on permeability it would be necessary to conduct similar permeability tests at a wider range of lateral pressure conditions.

7.3 Discussion of findings. The Phase 1 and Phase 2 investigations provided significant findings regarding the effect of concentrated TCE on some of the locally available clay soil materials in the Sharpe Army Depot area. The results demonstrated that the clay soils which were evaluated have low permeability which decreased when impacted by concentrated TCE. The findings also indicated that the clays appear to resist the permeation of TCE when saturated with water. The findings are significantly different from those generally reported in the literature. Results of past laboratory studies indicate that permeability of clays generally increased when organic solvents were used as the permeant (6, 7, 8, 14, 16). However, a decrease in permeability with organic solvents, similar to this current investigation, has been reported in a recent research study (19). The reason for this difference in response of the clays is not clearly understood and further investigations are currently in progress.

Several possible factors which may contribute to the lower permeability in the clay soils are as follows:

(1) Surface tension effects - One possible reason for the lower permeability with TCE could be that the relative immiscibility of the water and TCE (due to surface tension effects) is inhibiting the permeation of the TCE into the pore spaces in the soil which is saturated with water. The very low pore volume that permeated when TCE was used is a possible indication that the TCE is not penetrating into the soil pore spaces.

TABLE 13

COMPARISON OF PERMEABILITY AT LOW AND HIGH PRESSURE TEST CONDITIONS

SOIL TYPE: LOCAL SOIL AND VOLCLAY

WATER[1]				TCE[2]			
HIGH PRESSURE		LOW PRESSURE		HIGH PRESSURE		LOW PRESSURE	
MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)
0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00
0.06	2.47E-09	0.06	5.12E-09	0.08	6.21E-09	0.04	3.44E-09
0.12	4.01E-09	0.09	2.39E-09	0.15	5.00E-09	0.19	2.16E-09
0.28	5.29E-09	0.13	4.71E-09	0.20	3.93E-09	0.24	1.11E-09
0.38	5.68E-09	0.15	2.73E-09	0.28	3.38E-09	0.26	7.67E-10
0.46	3.93E-09	0.19	2.35E-09	0.30	1.78E-09	0.27	7.30E-10
0.51	2.24E-09	0.23	1.54E-08	0.31	5.68E-10	0.30	7.92E-10
0.60	6.72E-09	0.28	1.52E-09	0.37	1.99E-09	0.31	9.88E-10
0.69	5.91E-09	0.36	3.63E-09	0.38	6.09E-10	0.32	6.83E-10
0.77	4.29E-09	0.40	3.50E-09	0.39	9.86E-10	0.32	3.17E-10
0.85	4.67E-09	0.46	2.85E-09	0.40	4.57E-10	0.33	2.30E-10
0.92	4.30E-09	0.58	4.09E-09	0.40	2.39E-10	0.34	2.57E-10
1.00	4.68E-09	0.72	2.49E-09	0.41	1.62E-10	0.34	2.00E-10
1.06	3.78E-09	0.74	2.10E-09	0.41	2.90E-10	0.34	1.85E-10
1.10	3.78E-09			0.42	6.22E-10	0.34	2.70E-10
1.19	3.62E-09			0.42	2.07E-10		
1.26	3.02E-09			0.42	1.96E-10		
1.32	5.61E-09			0.43	9.20E-10		
1.38	3.54E-09			0.43	2.16E-10		
				0.43	2.09E-10		
				0.44	2.56E-10		
				0.44	2.48E-10		
				0.44	1.89E-10		
				0.45	2.43E-10		
				0.45	1.39E-10		
				0.45	1.56E-10		
				0.45	1.86E-10		
				0.46	1.48E-10		
				0.46	2.07E-10		
				0.46	1.50E-10		

1. WATER - 0.01N $CaSO^4$
2. TCE - 100% commercial grade solvent
3. MEAN PERM - mean permeability of triplicate tests

TABLE 14

COMPARISON OF PERMEABILITY AT LOW AND HIGH PRESSURE TEST CONDITIONS

SOIL TYPE: LOCAL CLAY

WATER[1]				TCE[2]			
HIGH PRESSURE		LOW PRESSURE		HIGH PRESSURE		LOW PRESSURE	
MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)
0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.01	0.00E+00
0.08	6.78E-09	0.12	5.71E-09	0.03	4.91E-09	0.13	1.16E-08
0.17	7.79E-09	0.23	1.13E-08	0.07	9.84E-10	0.25	5.15E-09
0.23	3.91E-09	0.35	1.16E-08	0.10	2.44E-09	0.43	7.53E-09
0.27	3.17E-09	0.44	7.27E-09	0.12	4.39E-09	0.45	6.11E-10
0.36	8.65E-09	0.56	9.71E-09	0.15	2.50E-08	0.46	6.90E-10
0.44	4.45E-09	0.70	7.38E-08	0.16	2.57E-09	0.46	8.24E-11
0.46	3.93E-09	0.94	5.67E-09	0.21	4.16E-09	0.49	2.06E-09
0.49	3.00E-09	1.14	5.41E-09	0.24	1.13E-09	0.49	1.67E-10
0.55	2.99E-09	1.20	5.87E-09	0.24	1.07E-09	0.49	3.64E-10
0.58	3.39E-09	1.34	5.93E-09	0.26	5.70E-10	0.50	4.98E-11
0.61	3.02E-09	1.50	6.40E-09	0.26	6.60E-10	0.51	4.67E-10
0.65	4.71E-09	1.54	3.54E-09	0.27	1.81E-10	0.51	1.72E-10
0.66	3.96E-09	1.80	4.68E-09	0.27	1.38E-10		
0.70	4.28E-09			0.27	1.79E-10		
0.74	3.26E-09			0.27	1.63E-10		
0.79	3.23E-09			0.27	1.87E-10		
0.83	3.21E-09			0.28	1.91E-10		
0.87	3.71E-09						
0.90	4.20E-09						
0.93	2.75E-09						
0.95	4.20E-09						
1.00	3.43E-09						
1.03	4.32E-09						
1.05	3.86E-10						

1. WATER - 0.10N $CaSO_4$ solution
2. TCE - 100% commercial grade solvent
3. MEAN PERM - mean permeability of triplicate tests

TABLE 15

COMPARISON OF PERMEABILITY AT LOW AND HIGH PRESSURE TEST CONDITIONS

SOIL TYPE: KAOLINITE

WATER[1] HIGH PRESSURE		WATER[1] LOW PRESSURE		TCE[2] HIGH PRESSURE		TCE[2] LOW PRESSURE	
MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)	MEAN PORE VOLUME	MEAN PERM[3] (CM/SEC)
0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00
0.36	5.92E-08	0.23	3.54E-08	0.03	2.64E-08	0.36	1.62E-08
0.59	4.85E-08	0.56	2.93E-08	0.16	2.10E-09	0.38	9.08E-10
0.67	1.96E-08	0.83	5.87E-08	0.16	9.35E-10	0.39	5.36E-10
0.79	2.54E-08	1.09	2.67E-08	0.17	9.55E-10	0.39	5.04E-10
0.92	2.80E-08	1.24	2.77E-08	0.17	5.63E-10	0.40	3.67E-10
1.10	8.73E-08	1.41	3.69E-08	0.17	3.28E-10	0.41	5.30E-10
1.33	9.65E-08	1.92	6.65E-08	0.17	2.85E-10	0.41	3.69E-10
1.44	3.55E-08	2.37	8.83E-08	0.17	2.78E-10	0.42	3.04E-10
1.56	8.03E-09	2.90	2.04E-09	0.17	2.64E-10	0.42	3.53E-10
1.60	6.76E-09	2.95	9.64E-09	0.18	2.43E-10	0.42	2.36E-10
1.78	3.22E-06	3.17	1.86E-08			0.43	2.81E-10
2.00	6.29E-08	3.47	4.96E-08			0.43	3.21E-10
2.17	9.68E-10	3.51	4.56E-09			0.43	3.45E-10
2.34	3.79E-08	3.72	4.41E-08			0.44	3.23E-10
2.68	3.26E-08					0.44	1.21E-10
2.77	2.56E-08					0.44	3.89E-10
2.94	2.69E-08						
3.19	3.30E-08						

1. WATER - 0.1N $CaSO_4$
2. TCE - 100% commercial grade solvent
3. MEAN PERM - mean permeability of triplicate tests

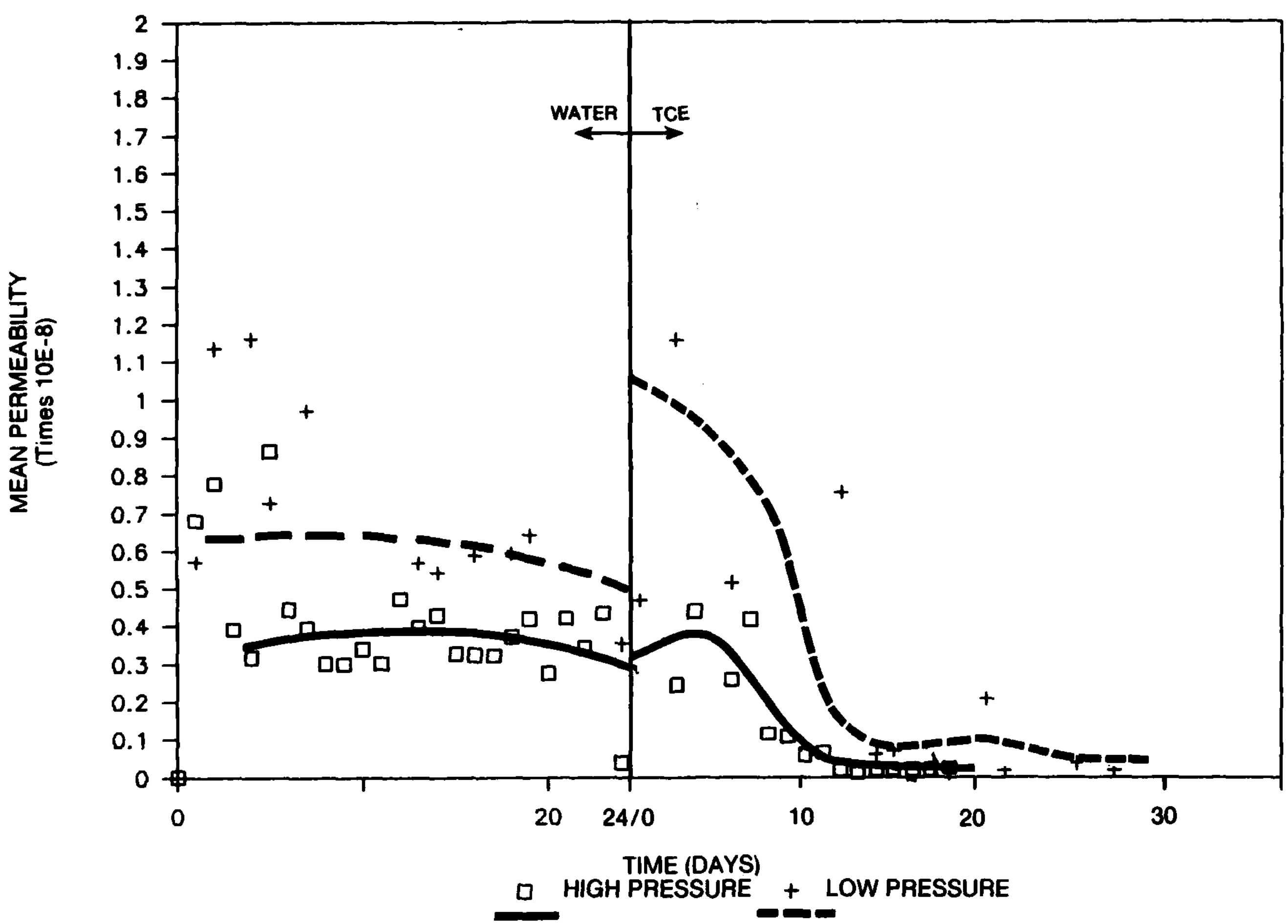


FIGURE 15 LOCAL CLAY: EFFECT OF LATERAL PRESSURE ON PERMEABILITY

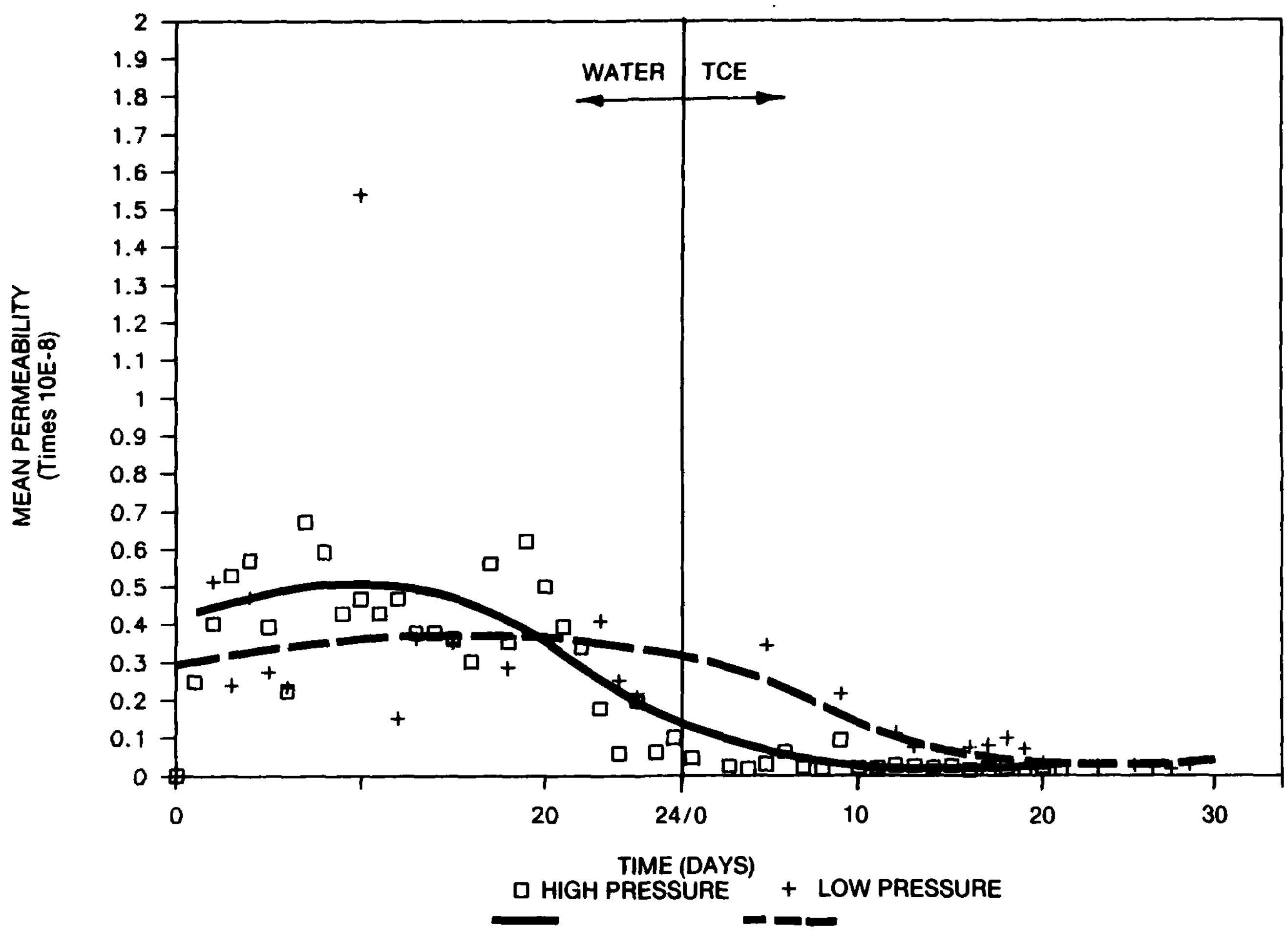


FIGURE 16 SOIL & VOLCLAY: EFFECT OF LATERAL PRESSURE ON PERMEABILITY

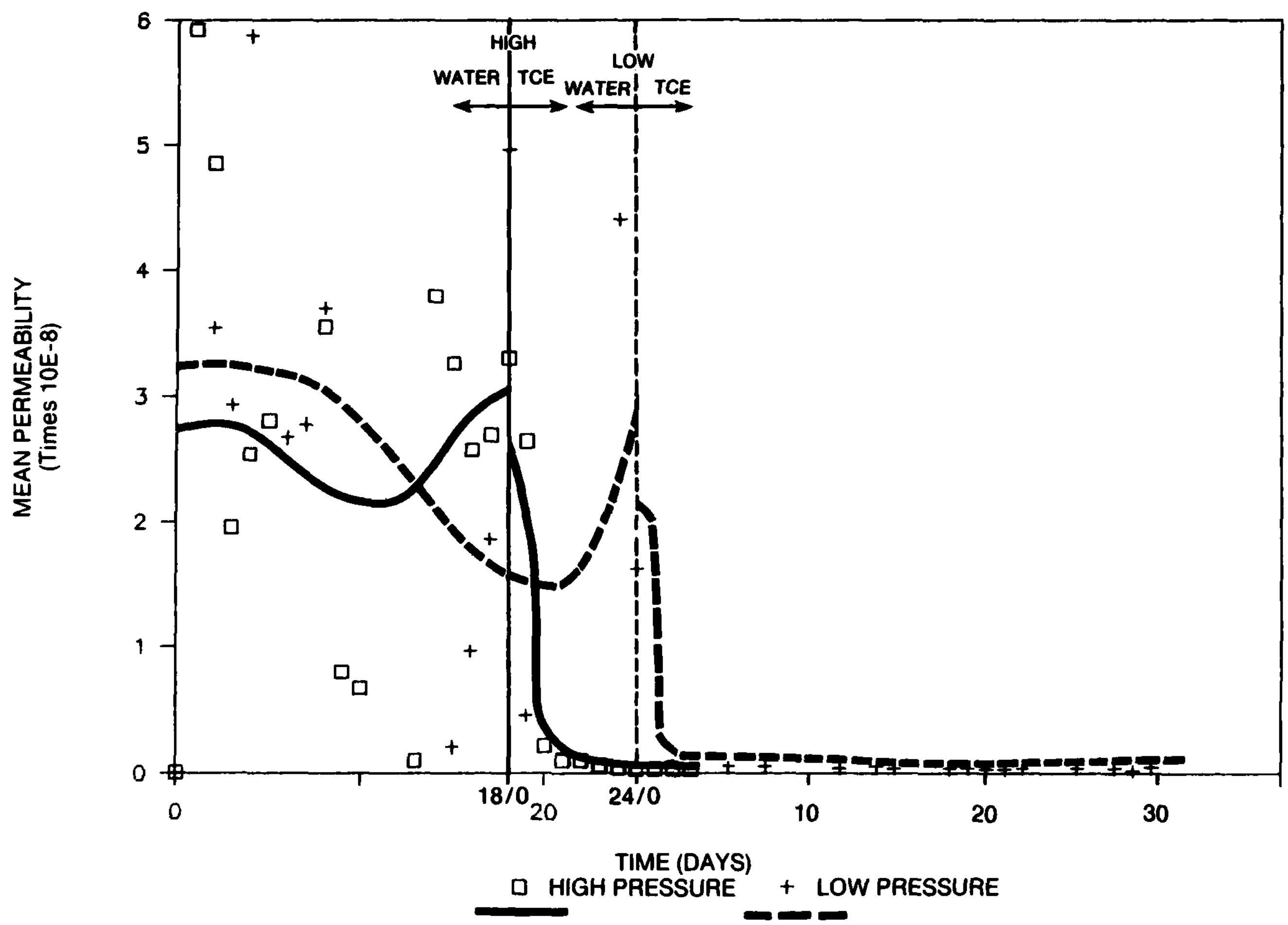


FIGURE 17 KAOLINITE: EFFECT OF LATERAL PRESSURE ON PERMEABILITY

(2) Partitioning effect - Another potential reason for this lower permeability with TCE may be due to a significant adsorption of the TCE on the soil matrix. This can result in minimal quantity of the TCE remaining in the liquid phase to permeate through the clay. The partitioning effect of the TCE between the solid phase (clay) and the liquid phase can be more significant because a 100 percent TCE solution was used, a large fraction of which may have been adsorbed on the soil.

7.4 Conclusions. Based on the laboratory scale investigations three potential clay liner materials to contain TCE contaminated soils, the following conclusions are made:

(1) The test apparatus and the test procedure used for the permeability tests were found to be effective, reliable, and convenient for conducting the clay liner permeability/chemical compatibility investigations.
(2) The permeability test results demonstrated a significant consistency in results between the triplicate columns.
(3) In the three clay oil types investigated, the effect of TCE on the permeability was very similar. In all cases, the permeability decreased by an approximate order of magnitude when the permeant was changed from water to TCE.
(4) A significant decrease in permeability was observed with TCE as the permeant as compared to water (0.01N $CaSO_4$). Several factors relating to impact of lateral pressure, surface tension effects at the TCE-water interface, and adsorption/partitioning effects were identified as potential causes and mechanisms responsible for the decrease in permeability. Additional testing would be required to determine the controlling mechanisms.
(5) Within a limited range, the lateral pressure did not appear to effect the permeability of the clay soils investigated. However, the finding is based on tests conducted at two lateral pressures. Additional tests using a range of different pressures would be required to fully define a relationship.
(6) The limited findings were very useful and established the need for further evaluation relating to effects of surface tension, partitioning, lateral pressure, and permeant concentration before projecting organic solvent and clay liner interactions.

(7) Based on the limited data from this investigation, it is not possible at this time to predict the feasibility of containing TCE-contaminated soil in a clay-lined secure landfill. However, the data does provide informtion regarding TCE-clay interactions and permeability effects under saturated soil conditions. If the recommended follow-on investigations are performed, considerable information can be generated that will enable the assessment of clay-lined secure landfills to contain TCE-contaminated soils (Subsection 7.5).

Further investigations as discussed are recommended to complete the evaluation of the clay soils as one of the potential installation/restoration technologies for the U.S. Army hazardous waste sites.

7.5 Recommendations. The issue that needs to be explored is identifying the possible factors or mechanisms which resulted in a lowering of the permeability of the clays when exposed to concentrated TCE. The scope of this laboratory investigation did not include additional testing to address this issue. The potential factors that may result in lowering of permeability with TCE are surface tension effects and partitioning effects. Recommendations for further evaluation are as follows:

(1) Conducting the test with a higher hydraulic gradient may help to break the surface tension effect at the interface of the TCE and water. It is also possible to evaluate the effect of the TCE-water immiscibility on permeability by conducting the test with TCE without presaturating the soil with water.

(2) To evaluate whether permeability of the clays is affected by the partitioning effect and the concentration of TCE in the permeant, it would be necessary to conduct a series of permeability tests using water (0.01N $CaSO_4$) containing different concentrations of TCE as the permeant. The concentration of TCE would be monitored in the effluent as well as in the soil sample before and after the tests. The mass balance of the TCE transferred can be calculated from the analytical results of the soil and the effluent. The permeability and mass balance data can be evaluated to determine the interaction of the TCE with the clay and its influence on the permeability of the clay soil.

APPENDIX A

CHEMICAL RESISTANCE OF VOLCLAY

5392A

AMERICAN COLLOID COMPANY
5100 Suffield Court • Skokie, Illinois 60077
(312) 966-5720 • TWX 910-223-0738 • TELEX 724-413
P.O. Box 696
Laconia, NH 03247
603/524-9294

November 2, 1984

Dr. Avijit Dasgupta
WESTON CONSULTANTS
Weston Way
West Chester, PA 19380

Re: Chemical Resistance of Volclay

Dear Dr. Dasgupta:

Per our phone conversation of November 1, there are a lot of interesting variables in the design of a seal made from a Volclay amended soil.

For chemical containment, the soil itself should be non-reactive such as silicon oxide, or similar.

For stability of the seal, a mixture of soil particle sizes is best, something from the middle area of the USDA trianuglar soil graph (copy enclosed). However gravel interferes with mixing and it requires additional Volclay to compensate for the presence of gravel. There is no problem with stones on top of or below the seal.

The effect of chemicals on a seal gets into a field that is essentially corrosion engineering, and the speed of reaction is analogous to fenders rusting off a car from the effects of road salt in the winter.

For pure chemicals we would automatically recommend Saline Seal (also called SS-100). However we also offer TFS-80 for chemical tank farms and SLS-70 for industrial waste landfills. In our general literature we limit the concentrations of chemicals to 10%, or 100,000 mg/l for the preceding. However there are many pure chemicals that SS-100, TFS-80 and SLS-70 would hold.

For some chemical tank farm service we sometimes offer a 30/30 warranty, meaning thirty years if no spill, and 30 days if there is a spill. The 30 days allows plenty of time for clean-up, and is used for those chemicals whose reactions are so severe that there is no other liner capable of doing as well.

For chemicals that are present in wastewater in concentrations lower than their saturation concentration in water, and where the TDS (total dissolved solids) is below 1%, or 10,000 mg/l then Volclay PLS-50 may be used. Testing at saturation concentrations is a bit tricky as a slight drop in temperature, or a slight change in barometric pressure, or a bit of evaporation of the water can put the solute over the critical point causing the formation of the pure chemical (say

(continued)

Dr. Avijit Dasgupta

trichloro ethylene) so that the test seal exposure changes from maybe 1100 mg/l to pure TCE. That kind of action is the classic mechanics of failure for membrane liners and results in either the classic waterline failure for light chemicals, or the classic lowest point failure for the heavy chemicals.

In generalities, a Volclay SS-100 in a 4" thick mixed blanket can be installed for about 75¢ per square foot, plus or minus 20%.

Also in generalities, Volclay PLS-50 in a 4" thick mixed blanket installs for about 40¢ per square foot, plus or minus 20%.

Enclosed are copies of Chemical Resistance of Clays, PVD's for Chemical Resistance Testing, a reference to ASTM D 2487, a copy of the USDA soils graph, and some Soil Evaluation Request forms. (There is no charge for the latter.)

We thank you for thinking of us and we would be happy to work further with you on this project. As other questions develop, please feel free to contact us.

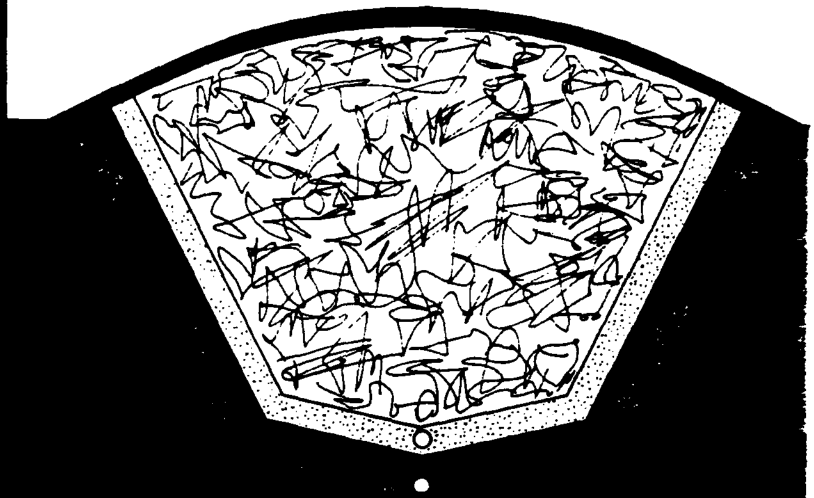
Very truly yours,

Bob Kingsbury

Robert P. Kingsbury
American Colloid Company
Eastern Regional Office

encl: a/s

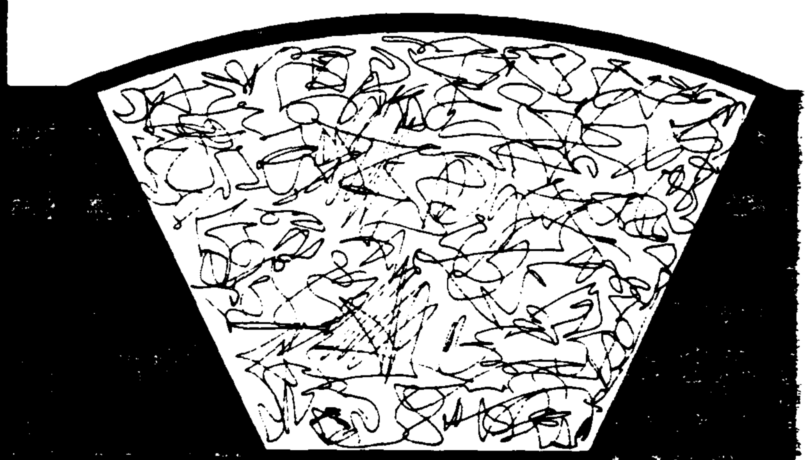
cc: Bob Scheflow
Joos Equipment Co.
P.O. Box 368
Paoli, PA 19301
215/644-5875



Volclay®

For lining and capping new landfills

For controlling leachate pollution from existing landfills



Volclay Landfill Sealants provide effective environmental protection from leachate pollution

American Colloid Company has been in the business of producing bentonite clay sealants since 1924. The company is the world's largest privately-owned bentonite mining company and operates processing plants in five states and several overseas locations. It has supplied bentonite sealant materials for almost one thousand landfill, lagoon and tank farm installations throughout the world.

Through its years of service to municipalities and other waste-containment operations, American Colloid has developed sealants specifically designed to be resistant to highly contaminated leachates commonly found in community waste or industrial landfills. Natural bentonite clays completely lose their sealing properties in the presence of landfill leachate through various contamination mechanisms. There are now four major types of Volclay landfill sealants:

SG-40 *for capping landfills*

SLS-71 for capping and lining municipal waste landfills

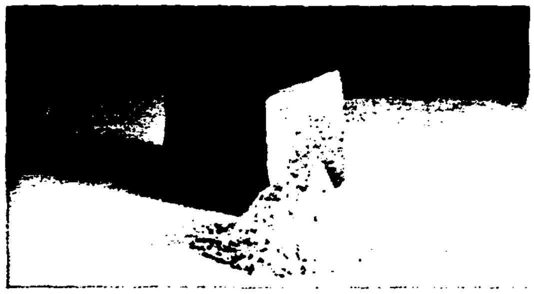
SLS-70 for industrial and hazardous waste landfills

SS-100 for extremely hazardous industrial landfills or lagoons

What is Volclay?

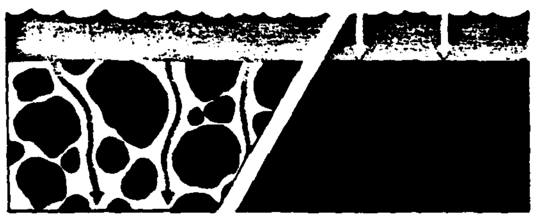
Volclay is produced from a special type of high swelling sodium montmorillonite (sodium bentonite). It has a unique molecular structure that captures water molecules, with the result that the bentonite expands up to 13 times its dry volume when wetted. The molecular structure is similar in several respects to ordinary clay, but the presence of sodium ions accounts for its ability to swell to a much greater volume than natural clay or other types of bentonite when saturated with water.

These unique swelling properties play a critical role in Volclay's effectiveness as a soil sealant.



How Volclay works

When a comparatively small amount of Volclay is mixed with soil and wetted, the Volclay particles swell and fill the voids between the soil particles. This creates a barrier that effectively stops further seepage through the soil. The swollen Volclay becomes a tough, highly flexible mastic that naturally expands and moves to self-seal any cracks that develop in the supporting soil. Thus, earth settlement and small ground movements which may damage membrane liners, native clay liners, or rigid liner systems, will not damage a Volclay-soil liner.



SPECIFICATIONS

VOLCLAY® BENTONITE

229-E (SLS-70)

6/1/84

SPECIFICATION

VOLCLAY BENTONITE

SLS-70

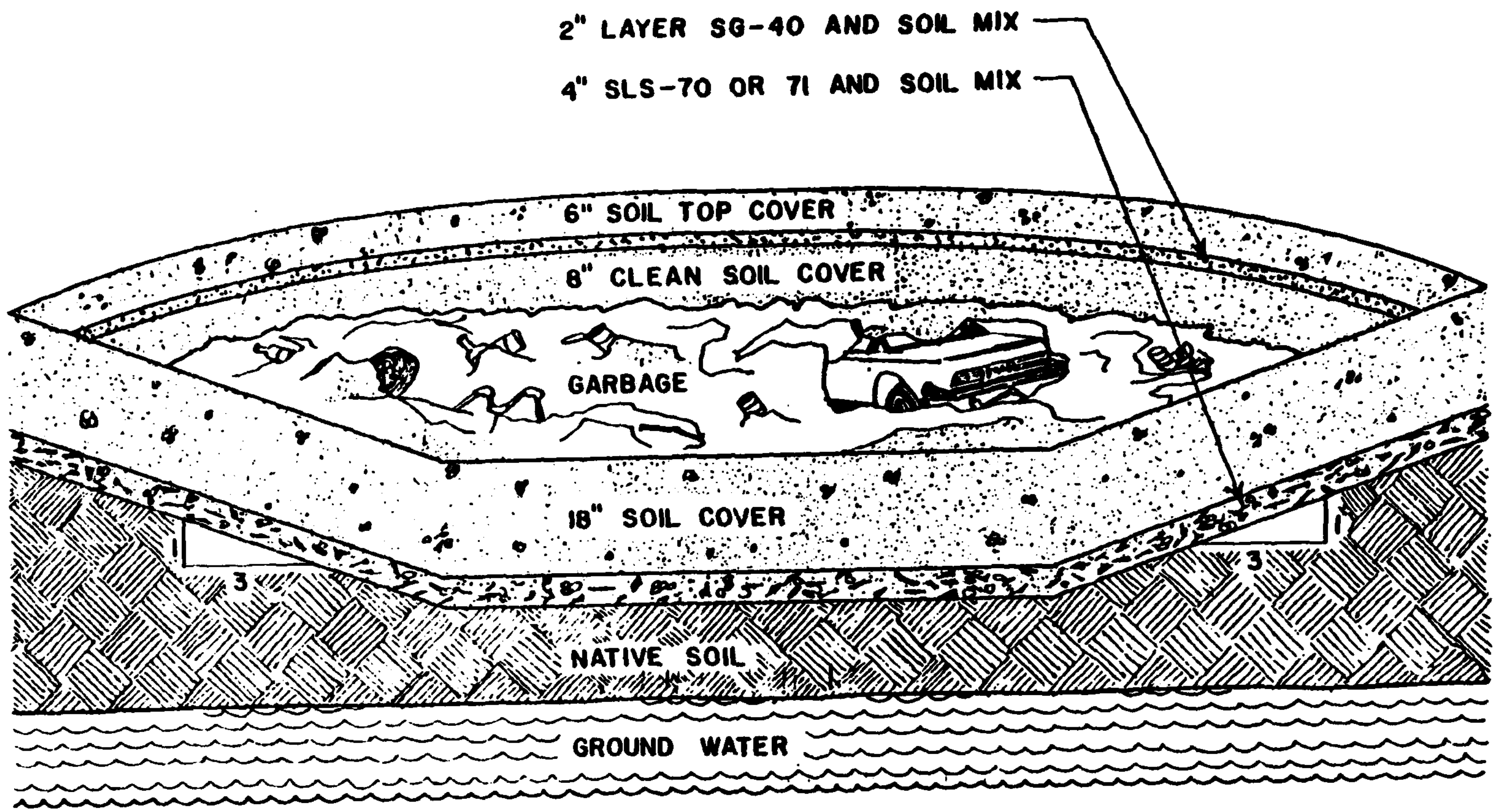
Volclay SLS-70 is a chemically and polymerically treated sodium based bentonite which is formulated as contaminant resistant bentonite. SLS-70 is intended for use in containing wastes with high levels of dissolved salts, acids or alkalis such as those generated in sanitary landfills containing chemical wastes.

These specifications are intended for use as general guidelines in formulating specifications tailored to a specific project. They are not intended as substitutes for detailed specifications which should be written to fit a particular project.

AMERICAN COLLOID COMPANY
Environmental Products Division

5100 Suffield Court • Skokie, IL 60077 • (312) 966-5720 • TWX 910-223-0738 • TELEX 724-413

LAND FILL



2" LAYER SG-40 AND SOIL MIX
4" SLS-70 OR 71 AND SOIL MIX
6" SOIL TOP COVER
8" CLEAN SOIL COVER
GARBAGE
18" SOIL COVER
NATIVE SOIL
GROUND WATER

SPECIFICATIONS
VOLCLAY® BENTONITE

American Colloid Company

Saline Seal 100

Chemical Compatibility Chart

	1%	10%	50%	100%
H_2O	-	-	-	N
Inorganic Acids	N	N	M	S
Inorganic Bases	N	N	M	S
Inorganic Salts	N	N	M	S
Organic Acids				
alcohols	N	N	N	M
aldehydes	N	N	M	S
amines	N	N	N	M
esters	N	N	N	S
ethers	N	N	N	M
Hydrocarbons				
benzene	N	N	N	M
zylene	N	N	N	M
toulene	N	N	N	M
Halogenated Hydrocarbons				
methylene chloride	N	N	M	S
ketones	N	N	M	S
chloroform	N	N	M	S
Carbon Disulfides	N	N	N	M
Nitrobenzene	N	N	N	M
Detergents & Other Cleaning Products	N	N	N	M
Fats, Grease & Oil	N	N	N	M
Oils & Fuels	N	N	N	M
Hydraulic Fluids	N	N	N	M
Miscellaneous				
antifreeze	N	N	N	M
glucose	N	N	N	M

Legend

N - No Effect
M - Mild Effect
S - Severe Effect

ACC
AMERICAN COLLOID COMPANY
Environmental Products Division
5100 Suffield Court • Skokie, IL 60077 • (312) 966-5720 • (312) 583-0400 • TWX 910-223-0738 • TELEX 724-413

Explanation of Legend

No Effect - The chemical additives encapsulating the bentonite would protect a mixed blanket of Saline Seal 100 and soil from any long term change in the coefficient of permeability.

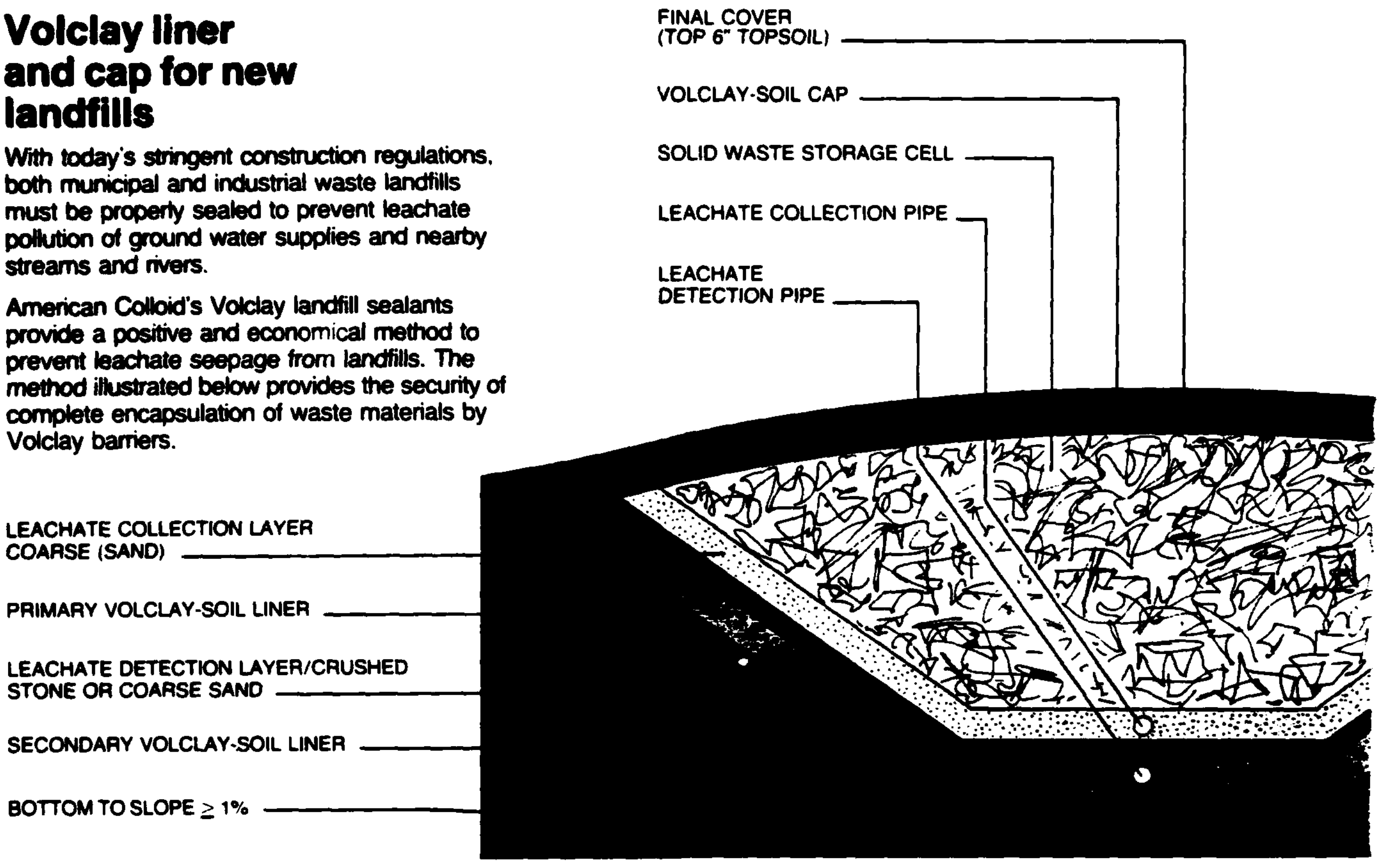
Mild Effect - During the initial exposure of a mixed blanket of Saline Seal 100 and soil to the leachate, a slight increase in the coefficient of permeability of the mixed blanket may, or may not, occur. After the initial exposure, the coefficient of permeability of the mixed blanket would remain essentially unchanged for the long term.

Severe Effect - The mixed blanket of Saline Seal 100 and soil would hold the leachate on a short term basis, but in the long term the liner would degrade over days, months, or years of exposure to the leachate. The liner degradation would consist of a loss of swellability of the bentonite, and, therefore, would not be recommended for the application.

Volclay liner and cap for new landfills

With today's stringent construction regulations, both municipal and industrial waste landfills must be properly sealed to prevent leachate pollution of ground water supplies and nearby streams and rivers.

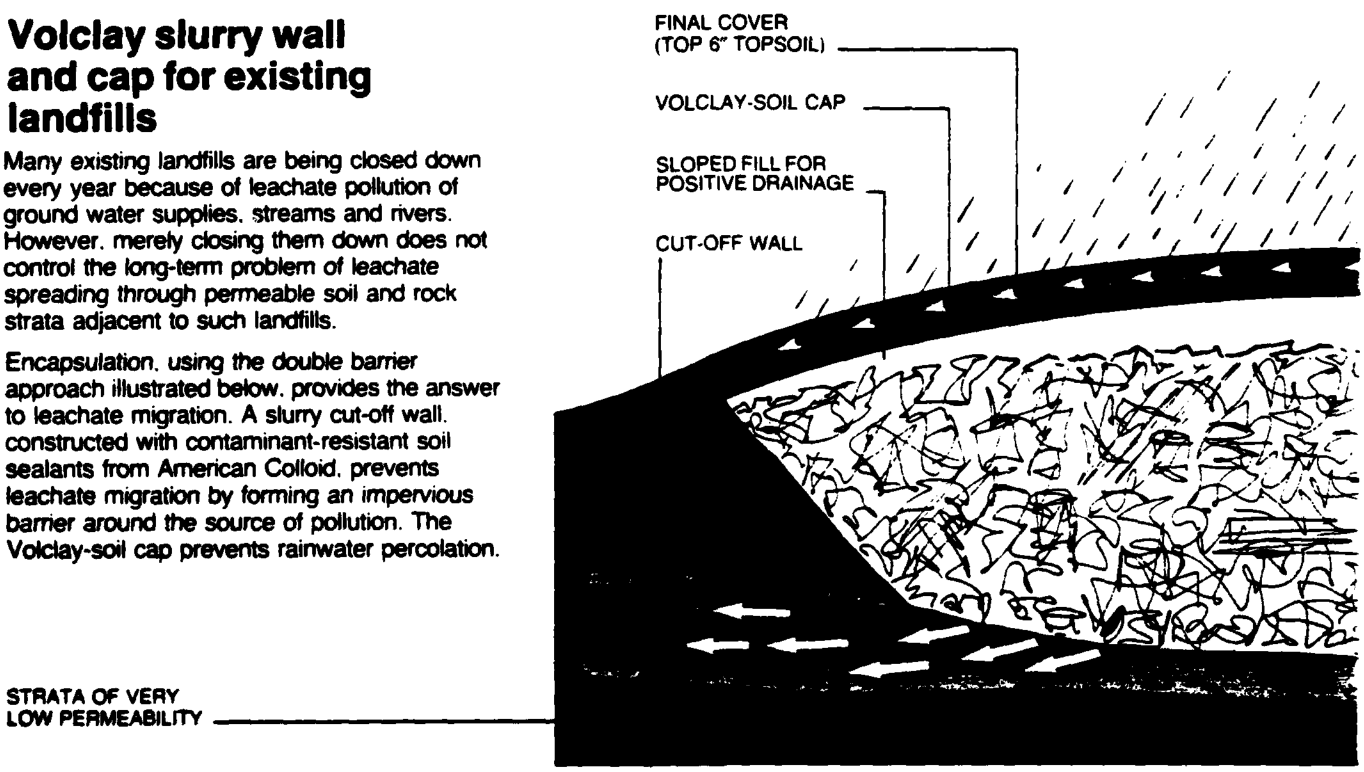
American Colloid's Volclay landfill sealants provide a positive and economical method to prevent leachate seepage from landfills. The method illustrated below provides the security of complete encapsulation of waste materials by Volclay barriers.

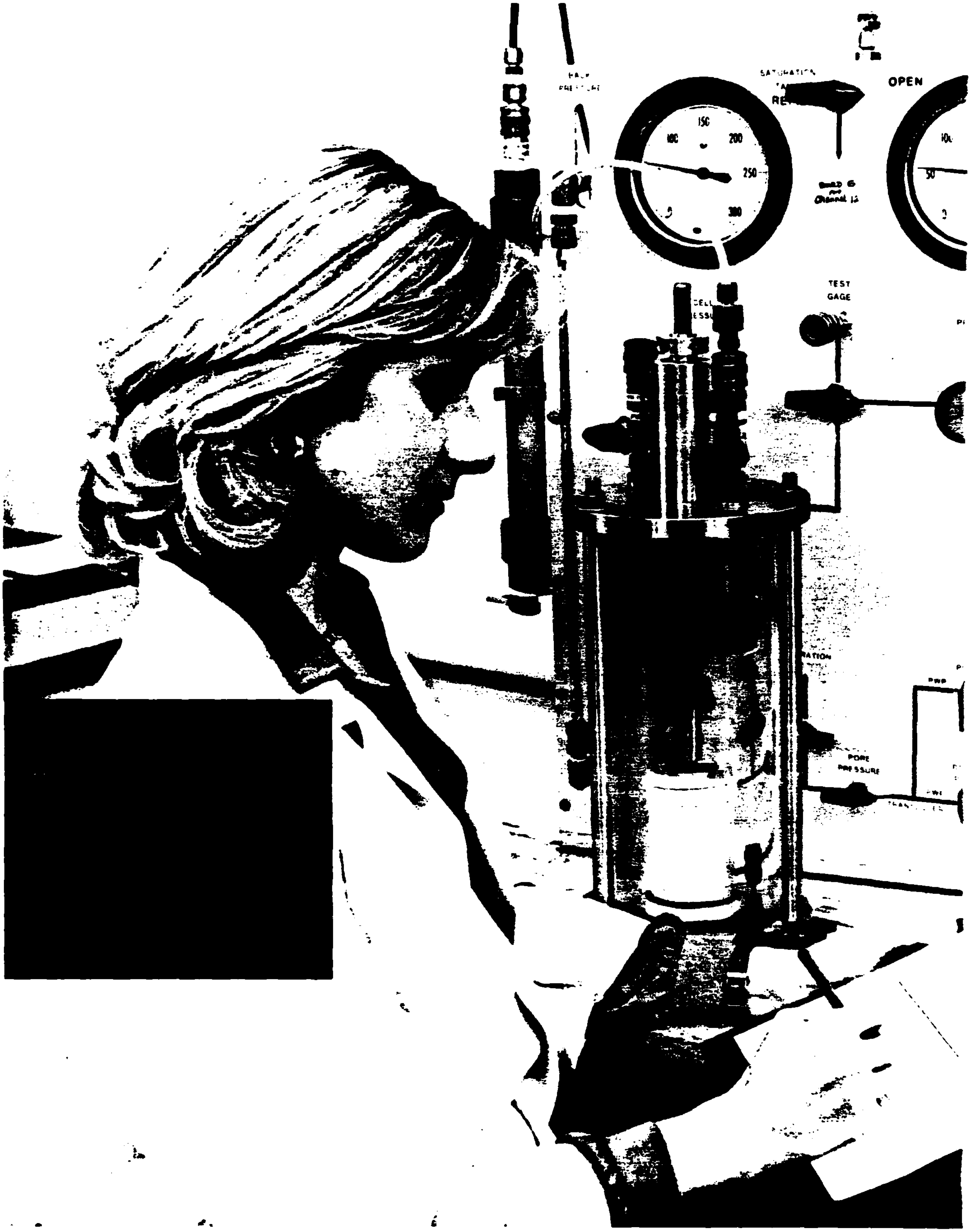


Volclay slurry wall and cap for existing landfills

Many existing landfills are being closed down every year because of leachate pollution of ground water supplies, streams and rivers. However, merely closing them down does not control the long-term problem of leachate spreading through permeable soil and rock strata adjacent to such landfills.

Encapsulation, using the double barrier approach illustrated below, provides the answer to leachate migration. A slurry cut-off wall, constructed with contaminant-resistant soil sealants from American Colloid, prevents leachate migration by forming an impervious barrier around the source of pollution. The Volclay-soil cap prevents rainwater percolation.

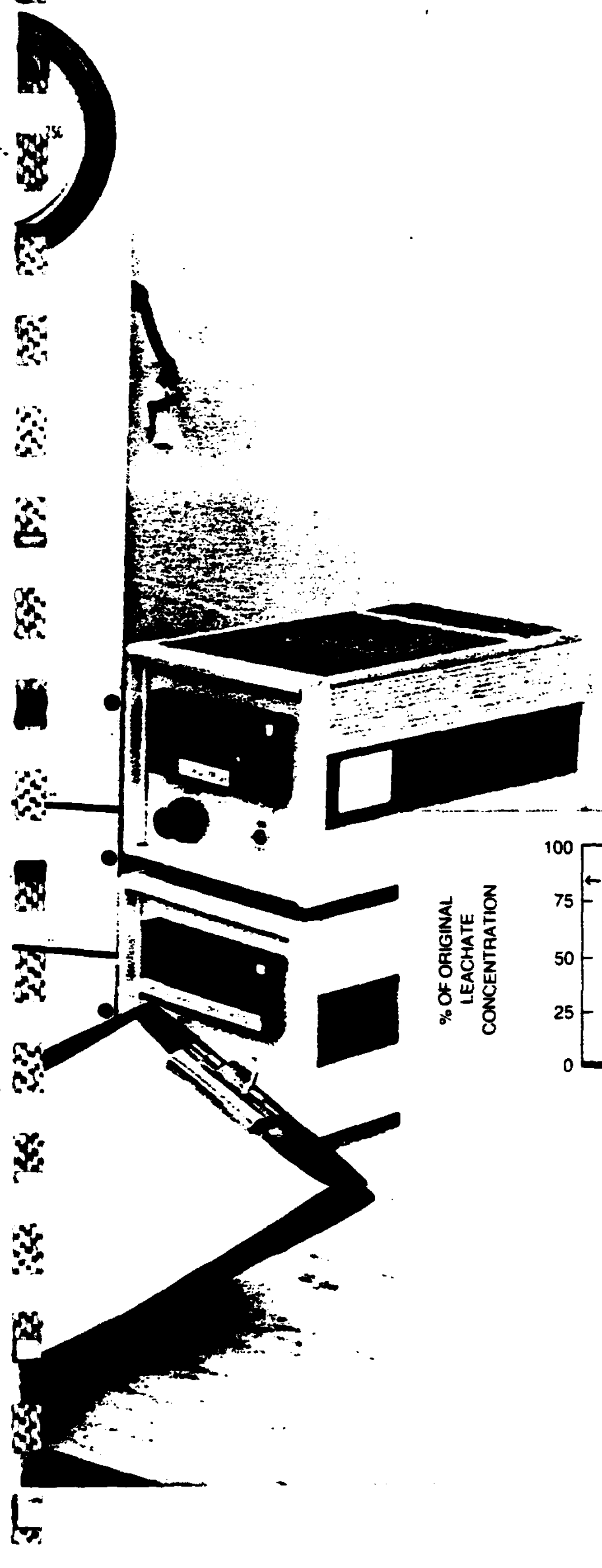



OPEN
TEST
GAGE
PORE
PRESSURE

Volclay Product Compatibility Testing

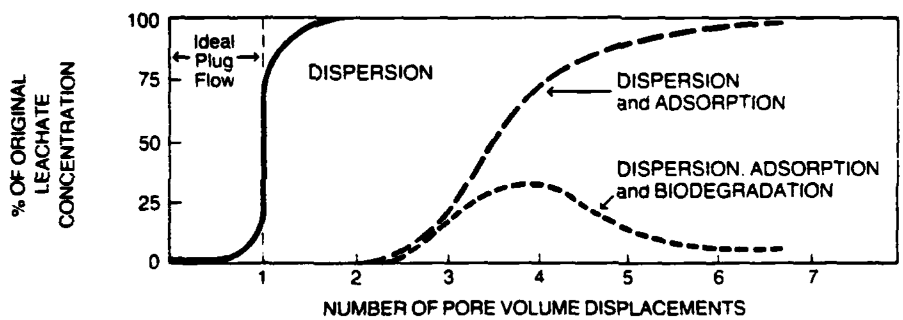
American Colloid Company's contaminant-resistant products (SLS-70, SLS-71 and Saline Seal 100) have been extensively tested at American Colloid's laboratory and at independent laboratories against numerous organic and inorganic leachates that are known to either stop or reverse the swelling of untreated bentonite. Compatibility testing has repeatedly shown that specially-treated contaminant-resistant Volclay products outperform other untreated bentonite products. In addition to laboratory testing, these contaminant-resistant products have been used in hundreds of different projects and applications throughout the world with excellent success.

Our on-going testing program has resulted in a broad data base from which product recommendations are made for landfill applications.



Pore Volume Displacement Method

The sealing efficiency of a contaminant-resistant Volclay product with a specific leachate is determined by means of a permeability test. To conduct a permeability test properly, sufficient quantity of a leachate must contact and pass through a Volclay-soil specimen in a periameter unit until such time that steady state permeability conditions exist. This generally requires two to six pore volume displacements, depending on the leachate constituents. Reliable testing for contaminant-resistance over the life of a project commonly requires upwards of 20 pore volume displacements.



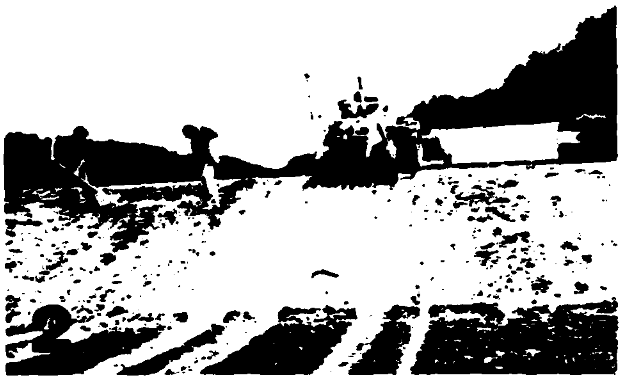
(Curve per Geraghty & Miller Groundwater Consultants)

The diagram above shows what typically occurs during the early stages of a permeability test prior to attaining steady state conditions. Accelerating the permeability test by means of unrealistic hydraulic gradients or unrealistic contaminant concentrations will not provide useful information about the long term effectiveness of such products in actual field conditions. Thus, permeameter test columns at American Colloid's laboratory are run at hydraulic gradients of 5 to 20, which is the range in which Darcy's Law is valid. In addition, contaminant-resistant Volclay products are exposed to *actual* leachate concentrations for whatever duration is necessary to achieve steady-state conditions.

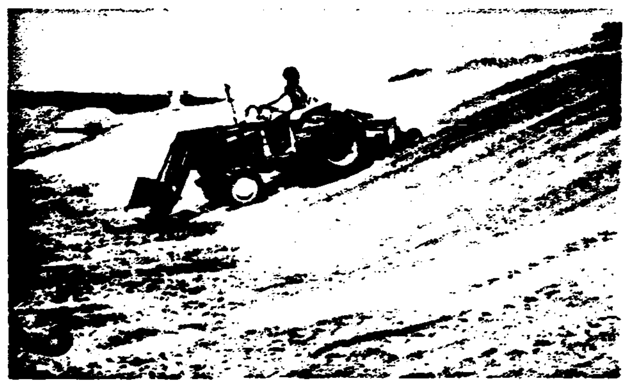
Applying **Volclay** is easy, can be accomplished with readily-available mechanized equipment

Volclay mixed blanket application method

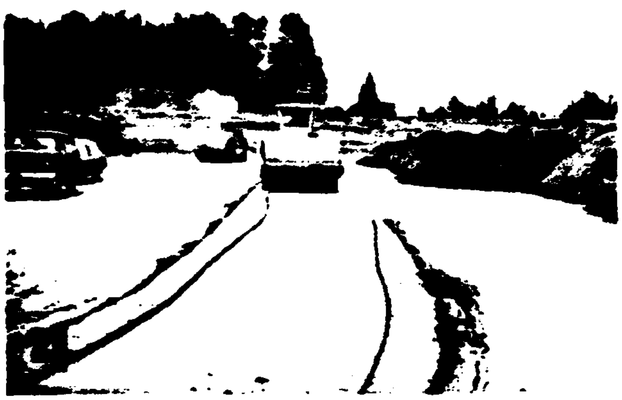
Soil Conditioning After finish grading has been achieved and excessively large rocks (larger than ⅓ the thickness of the Volclay-Soil liner) have been removed. a water truck is used to adjust the soil to optimum moisture content. (8%-16% for most soils)



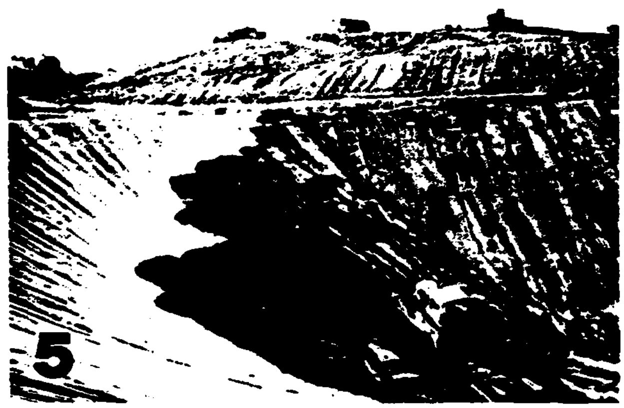
Application of Volclay Sealant Readily available equipment such as a bulk lime spreader or seed spreader may be used to apply the required amount of Volclay sealant. Manual application is also practical. Bags of Volclay weighing 100 lbs. are placed in a marked grid pattern on the surface of the area to be sealed. Bags are broken open and spread manually over the grid according to the specified application rate per square foot of area.



Blending Volclay with Soil A rotary tiller or roto tiller. with an adjustable depth control provides vigorous mixing which is necessary to achieve a homogeneous Volclay-soil blanket. An agricultural disc is sometimes used initially to loosen the soil prior to rototilling.



Compaction The Volclay-soil mixture is compacted to a minimum of 85% Modified Proctor with a wobble wheel or steel wheel vibratory roller. A sheeps foot roller should not be used.



Top Cover A 12" to 18" porous cover is provided over Volclay-soil bottom liners to facilitate drainage to collection pipes. An 18" layer of native soil is applied over a Volclay-soil landfill cap to provide a protective cover.

Slurry Trenching ... An effective barrier to leachate pollution from existing landfills

Preventing leachate migration from existing landfills is possible with the slurry trenching construction technique and American Colloid's contaminant-resistant sealants. In the illustration, note that the trench is keyed into a natural impervious layer which prevents further migration of the leachate. The trench is composed of a well-graded backfill and contaminant resistant SLS-70 or Saline Seal 100.

SPECIAL VOLCLAY FOR SLURRY TRENCHES

	DESCRIPTION	TYPICAL MIX RATIO
Slurry Ben 90	A 90 barrel yield* 200 mesh bentonite	1 part Volclay to 15 parts water
Slurry Ben 125	A 125 barrel yield* bentonite	1 part Volclay to 22 parts water
Saline Seal 100	A 70 barrel yield* Wyoming bentonite to be used specifically to resist contamination in excess of 100.000 PPM TDS	1 part Volclay to 12 parts water

* Based on API

Constructing the slurry trench

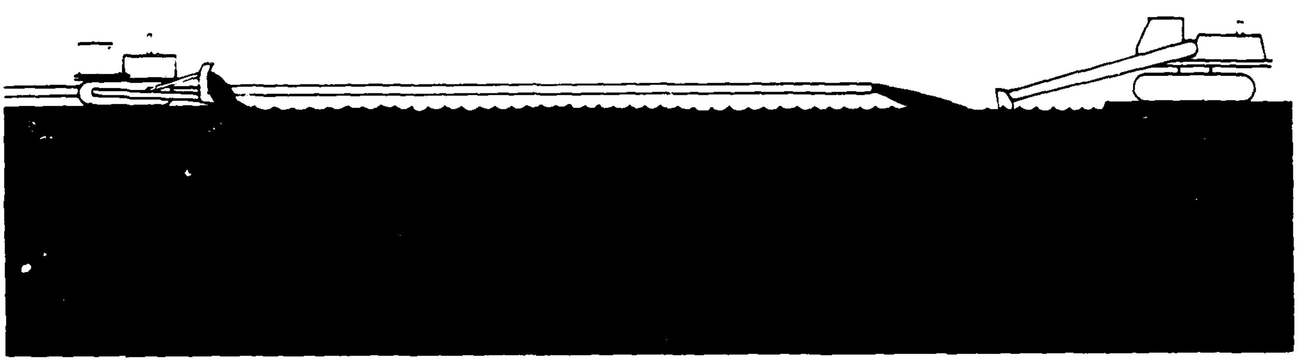
The first step in slurry trench construction is to excavate a trench from grade to approximately three feet into an aquaclude such as bed rock or an impervious clay strata, while keeping the trench filled with a Volclay-and-water slurry. In the illustration below, the hydraulic excavator has "keyed" the trench into an impervious clay layer under a full head of bentonite slurry.

Because the Volclay bentonite slurry has a slightly higher specific gravity than water, it creates a positive hydrostatic head that stabilizes the sides of the trench to prevent collapse. The Volclay bentonite slurry also interacts with the sides of the trench to create a seal that tends to hold soil particles together. Because of this, it is possible to excavate a trench 3 feet wide and over 250 feet deep (although 20 to 50 feet is more common) with minimal danger of sidewall collapse.

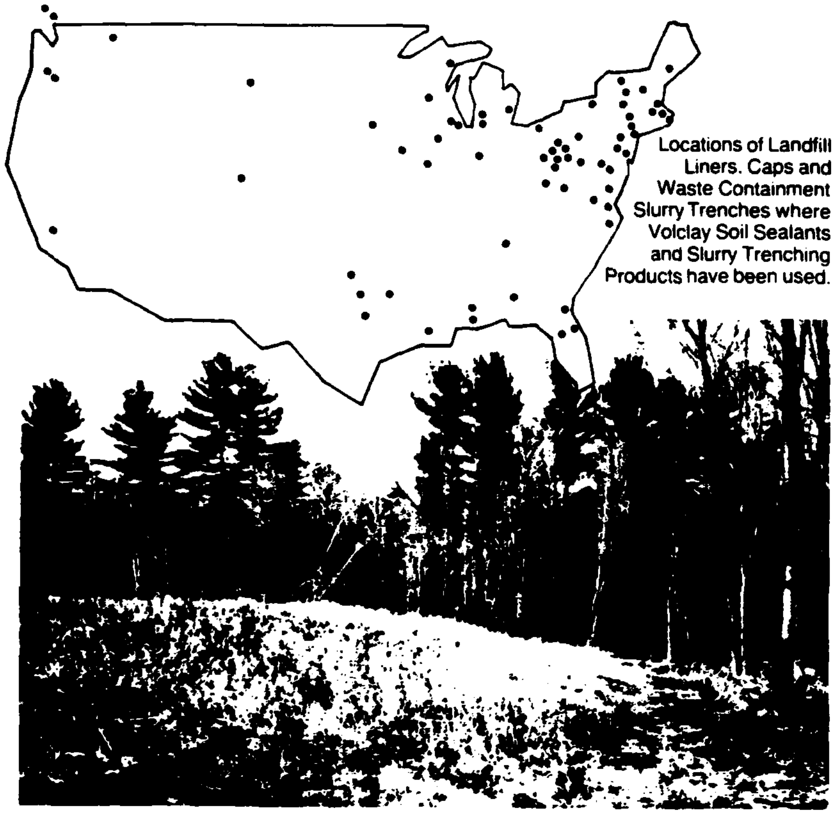
As trench excavation continues, additional slurry is added to compensate for each bucket of spoil removed.

After the trench has been keyed, the final step of backfilling can begin. The backfill consists of additional Volclay and soil which have been mixed in the proper ratio to provide an impervious barrier. In the illustration, controlled back-filling has begun where the trench starts. The addition of backfill displaces spent slurry which is then pumped out and either returned to the trench or disposed of as excavation proceeds.

Proper backfill is the key to long-term barrier effectiveness. American Colloid laboratory analysis can make an advance determination as to whether the spoil from the trench is suitable for backfill. If not, they will recommend a backfill, the right Volclay product, and the proper mix for an optimum barrier wall.



Volclay® Sealants are protecting communities all over the country from leachate pollution



This beautiful setting could be a park or just a green field. In actuality, it is a landfill of leather scrap over 30 feet deep. The fill is encapsulated by a Volclay liner and protected from rainwater intrusion by a Volclay Cap. Because the leather scrap produces a very springy fill, only Volclay with its flexible membrane and its ability to self-seal after flexure was able to meet the stringent requirements for this landfill.

Volclay also minimizes the escape of gases from the landfill and provides a beneficial substrate for grass-type foliage. It requires only annual mowing to inhibit the growth of woody plants whose roots might penetrate the Volclay membrane.

For additional information on product specifications, test data and test reports contact:

AMERICAN COLLOID COMPANY

Environmental Products Division

5100 Suffield Court • Skokie, Illinois 60077 • 312/966-5720

Printed in U.S.A. Form No. 5M684

APPENDIX B

REFERENCES

5392A

APPENDIX B

REFERENCES

1. Weston Inc., Roy F. Clay Liner Performance: An Assessment of Current Research Activities and Needs. Report prepared for USATHAMA, Task Order 5, Contract No. DAAK1182-C-0017, January 1984.

2. Personal communication with Dr. J. Jeffrey Peirce, Department of Civil Engineering, Duke University, Durham, North Carolina, November 1984.

3. Olson, R.E. and Daniel, D.E. Measurement of Hydraulic Conductivity of Fine-Grained Soils. ASTM STP 746, 1981.

4. Monserrate, M. Evaluation of Hydraulic Conductivity of Two Clays Exposed to Selected Electroplating Wastes. M.S. thesis directed by J. Peirce, Civil Engineering, Duke University, Durham, North Carolina, September 1982.

5. Daniel, D.E., et al. Fixed-Wall vs. Flexible-Wall Permeameters. ASTM Special Technical Publication 874. In print.

6. Foreman, D.E. and Daniel, D.E. Effects of Hydraulic Gradient and Method of Testing on the Hydraulic Conductivity of Compacted Clay to Water, Methanol and Heptane. Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste Sponsored by EPA. EPA-600/9-84-007, April 1984.

7. Anderson, D., et al. Effect of Organic Fluids on the Permeability of Clay Soil Liners. Proceedings of the EPA-sponsored Eighth Annual Research Symposium. Ft. Mitchell, Kentucky, March 1982.

8. Acar, Y.B., et al. The Effect of Organic Fluids on Hydraulic Conductivity of Compacted Kaolinite. Research Report on Geotechnical Engineering. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana, September 1984.

9. Acar, Y.B., et al. The Effect of Organic Fluids on the Pore Size Distribution of Compacted Kaolinite. Research Report on Geotechnical Engineering. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana, September 1984.

10. Acar, Y.B., et al. Transport of Organic Contaminants and Geotechnical Properties of Fine-Grained Soils. Research Report on Geotechnical Engineering. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana, September 1984.

11. Rad, N.S. and Acar, Y.B. Study of Membrane-Permeant Compatibility. Research Report on Geotechnical Engineering. Department of Civil Engineering, Louisiana State University, Baton Rouge, Louisiana, September 1984.

12. Fang, H.Y., et al. Effect of Pore Fluid on Soil Cracking Mechanisms. Proceedings of the Fifth ASCE Engineering Mechanics Division Specialty Conference. Laramie, Wyoming, August 1984.

13. Alther, G., et al. Influence of Inorganic Permeants Upon the Permeability of Bentonite. Proceeding of the ASTM Symposium on Impermeable Barriers for Soil and Rock, Denver, Colorado, June 1984.

14. Green, W.J., et al. The Swelling of Clay-Soils in Water and Organic Solvents. Research report, Department of Civil Engineering, Colorado State University, Fort Collins, Colorado.

15. Daniel, D.E. Effects of Organic Chemicals on the Hydraulic Conductivity of Compacted Clay. Proceedings of the International Symposium on Clay Barriers for Isolation of Toxic Chemical Wastes, Stockholm, Sweden, May 1984.

16. Brown, K.W., et al. The Influence of Selected Organic Liquids on the Permeability of Clay Liners. EPA-sponsored research report. Department of Soil and Crop Sciences. Texas Agricultural Experiment Station, College Station, Texas, May 1983.

17. Brown, K.W., et al. Permeability of Compacted Soils to Solvent Mixtures and Petroleum Products. Proceedings of the EPA-sponsored Tenth Annual Research Symposium on Land Disposal of Hazardous Waste. Ft. Mitchell, Kentucky, April 1984.

18. Green, W.J., et al. Clay Soils Permeability and Hazardous Waste Storage. Jour. Water Poll. Control Fed., Vol. 53, No. 8, August 1981.

19. Bowders, J.J., The Influence of Various Concentrations of Organic Liquids on the Hydraulic Conductivity of Compacted Clay. Ph.D. dissertation, Civil Engineering, University of Texas, Austin, Texas, August 1985.

20. Haxo, H.E. Effects of Liner Materials of Long-term Exposure in Waste Environments. Proceedings of the EPA-Sponsored Eighth Annual Research Symposium on Land Disposal of Hazardous Wastes, March 1982.

21. Peirce, J.J. et al. Leaching of Electroplating Wastes through Clay Liners. Proceedings of Annual Meeting of AICHE. December 1981.

22. Peirce, J.J. et al. Termination Criteria for Clay Permeability Testing. Journal of Geotechnical Engineering Division, ASCE. Submitted in August 1984.

23. Peirce J.J. et al. Effects of Inorganic Leachates on Clay Liner Permeability. Final Report. EPA Cincinnati Contract No. 68033149, 24-1, September 1984.

24. Kugelman, I.J. et al. Influence of Industrial Wastes on the Geotechnical Properties of Soils. Toxic and Hazardous Waste. Butterworth Publishing. June 1983.

WESTON
DESIGNERS CONSULTANTS

DISTRIBUTION

Defense Technical Information Center Cameron Station Alexandria, VA 22314	14 copies
Defense Logistics Study Information Exchange US Army Logistics Management Center Fort Lee, VA 23801	2 copies
Commander US Army Toxic and Hazardous Materials Agency Aberdeen Proving Grounds Aberdeen, MD 21010-5401	14 copies

END

12-86

DTIC